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A Comparative Study of Soviet vs. Western Helicopters

Part 2 - Evaluation of Weight, Maintainability, and Design Aspects of Major Components

W. Z. Stepniewski
International Technical Associates, Ltd.
Upper Darby, Pennsylvania

R. A. Shinn
Aeromechanics Laboratory
AVRADCOM Research and Technology Laboratories
Ames Research Center
Moffett Field, California

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Preface

When the outline of "The Comparative Study of Soviet vs. Western Helicopters" was first being formulated, it was contemplated that in addition to the general comparison of the rotorcraft as a whole contained in Part I, it would be desirable to obtain a deeper insight into the design philosophies of the major components of the compared aircraft.

However, it soon became apparent that a complete study along those lines would grow into an awesome task exceeding the intended scope and volume content of the project. Furthermore, much of the technical information required for such an undertaking was simply not available, at least as far as Soviet helicopters were concerned.

Consequently, it was decided to limit the component comaprison to the following: (1) Weights – In addition to ascertaining the various trends regarding the weights of the major components, three methods of weight-prediction (one Soviet and two Western) were critically examined, and the results were compared to the actual weights. (2) Maintainability – Although the scope of this investigation is limited chiefly due to the lack of verifiable information on Soviet helicopters, it is believed that there is good authority for the approach to the maintainability aspects regarding differences and commonalities exhibited by the two schools of design. (3) Evaluation of the overall component design – The design evaluation technique used in this study represents an initial attempt to develop a quantitative method for judging and comparing the design merits of the components. Because of its preliminary nature, this task was limited to illustrating the proposed approach on the examples of main-rotor blades and hubs.

In the book "Helicopters – Selection of Design Parameters" by Tishchenko et al, which is used frequently as a reference, configurations of large transport helicopters were rated in the following order regarding their payload-carrying capabilities: first, single rotor; second, side-by-side; and third, tandem. A thorough critical examination of that rating system would grow into a design and sizing study. However, by showing that the relative weight trends of major helicopter components constitute first-order inputs with respect to placement in a particular class, it was possible to show that if the relative-weight trends exhibited by Western designs rather than those considered by Tishchenko, et al were applied, the tandem would probably excel in relative payload capabilities when compared with the single-rotor configuration.

As in the case of Part I, "General Comparison of Designs," this evaluation was prepared with the assistance of various individuals and organizations. In this respect, the authors and associate editor wish to express their gratitude to Dr. R.M. Carlson, Director of the U.S. Army Aviation Research and Technology Labs for his encouragement and valuable suggestions. Thanks are also due to Dr. M.P. Scully of the same organization; and to Messrs. R.H Swan, A.H. Schmidt, and J.S. Wisniewski from Boeing Vertol for their valuable contributions. Finally, it should be noted that Mr. R.A. Shinn, who served as monitor of Part I of this project, also served as coauthor of this volume, while Mr. W.D. Mosher of the U.S. Army Aviation Research and Technology Labs served as monitor of Part II. Mrs. Wanda L. Metz, associate editor, was also responsible for the composition of both parts of this study.

W.Z. Stepniewski
R. A. Shinn

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List of Symbols

AR	aspect ratio
a	adjustment factor, also design coefficient
CF	centrifugal force, lb or m.ton
C_1	constant accounting for such fuel items as auxiliary fuel system, pressurization, and inflight fueling
C_2	crashworthiness and survivability factor for the fuel system
c	blade chord; ft or m
chp	horsepower; in metric units
D	diameter; ft
F_{bt}	fuel tanks and supporting structure tolerance factor
F_{cb}	factor denoting the type of flight control operating mechanism
F_{cp}	flight control ballistic tolerance factor
F_{cr}	crashworthiness factor (fuel tanks)
F_{lo}	lubrication oil-system factor
FF	fuel flow; lb/hr
G_t	total fuel tank capacity; gal
I_{ramp}	factor denoting ramp presence
I_{rlg}	landing-gear retraction factor
I_{slp}	factor denoting blade stiffness inplane influence on skid landing gears
K_t	configuration factor (single rotor = 1.0; tandem rotor = 1.3)
k	direct weight coefficient
k^*	indirect weight coefficient
k_b	coefficient related to number of blades
k_d	drag coefficient
k_{mad}	design coefficient, where m = material; a = design; and d = development stage
k_r	rotor-type coefficient
L	fuselage length; ft
L_a	cabin length from nose to end of cabin floor; ft
L_{rw}	rampwell length; ft
M	moment, or torque; ft-lb or kg-m
N_{ref}	total installed referred horsepower, in chp

n	number
n_{clf}	crash load factor
n_{lf}	limit load factor (at design gross weight)
n_{llf}	landing load factor
n_{ult}	ultimate load factor
n_z	$n_z \equiv W_{gr} \times n_{lf}/(W_{gr})_{max}$
n_{zl}	$n_{zl} \equiv W_{gr} \times n_{llf}/(W_{gr})_{max}$
R	rotor radius; ft or m
R	$R \equiv R/16m$
r	radius of blade attachment fittings; ft
rpm	revolutions per minute
S_f	fuselage wetted area; ft^2 or m^2
SHP	shaft horsepower; hp or chp
sw	specific weight; psf
T	power to rpm ratio
t	blade thickness at 25% R; ft
V	flight velocity; kn
V_t	tip speed; fps or m/s
W	weight; lb or kg
W_a	actual weight; lb or kg
W_{gr}	gross weight; lb or kg
W_{gr_h}	hovering gross weight; lb or kg
W_p	predicted weight; lb or kg
W	relative component weight, $W \equiv W'_{cn}/W_{gr}$
W_{pl}	relative payload, $W_{pl} \equiv W_{pl}/W_{gr}$
W_{pl_o}	zero-range relative payload (weight output), $W_{pl_o} \equiv W_{pl_o}/W_{gr}$
w	disc loading; psf or kg/m^2
z	number of stages in main-rotor drive
α	configuration coefficient
α_λ	blade-type coefficient
α_Ω	nonuniform torque coefficient
ΔCG	center of gravity range at W_{gr}; ft
λ	blade aspect ratio
λ	$\lambda \equiv \lambda/18$

λ_o	blade reference aspect ratio
ν	first natural blade frequency in flap bending, per rev
σ	rotor solidity

Subscripts
(unless called otherwise in parts of complete symbols)

ai	air induction
ad	airduct
ar	air outlet
av	average
b	number of blades
bc	boosted controls
bg	body group
bl	blade(s)
c	cowling
cc	cockpit controls
clf	crash load factor
cn	component number(s)
des	design
dr	drive
ds	drive system
dsh	drive shaft
eg	electrical group
em	engine mounts
eng	engine(s)
eq	equivalent
eqp	equipment
eqp_o	other equipment
f	fuselage
fc	flight controls
fs	fuel system
f_{s-t}	fuel system less tank
ft	fuel tank(s)
fu	fuel
fw	wetted area
gb	gearbox
gtr	tail-rotor gearbox
h	hub
ht	horizontal tail
igb	intermediate gearbox
lg	landing gear
max	maximum
mc	manual controls
mgb	main-rotor gearbox
mr	main rotor
mrc	main-rotor controls
msc	main-rotor system & hydraulics
n	nacelles
$n\text{-}c$	nacelle less cowling
nw	wetted nacelle(s)
pl	payload
pmr	per main rotor
pss	propulsion subsystem
ref	referred
rfc	rotor flight controls
rsc	rotor system controls
rlg	landing-gear retraction
rot	rotor
s	skid
sbs	side-by-side
sh	shaft(s)
sp	swashplate
sr	single rotor
ss	subsystem
TO	takeoff
tan	tandem
tot	total
tr	tail rotor
trr	transmission rating
ult	ultimate
vt	vertical tail
w	wheel
wl	wheel-type landing-gear legs
Σ	summation, or overall

Chapter 1
Introductory Considerations

1.1 Objectives

As a follow-up to the general comparison of the helicopter designs performed in Part I of this study, Part II is devoted to a comparative analysis of the major components of Soviet vs. Western helicopters.

In principle, it would be desirable to examine in some detail the following aspects of major components:

(a) conceptual design approach
(b) maintainability and producibility
(c) weight-prediction methods, and actual weight trends.

However, with the limited knowledge available regarding current Soviet helicopters, it would be difficult, or almost impossible, to perform a comprehensive, in-depth analysis of items (a) and (b). With respect to weight aspects, the situation is much better since, in Ref. 1, not only are the weight prediction formulae given for major components – presumably used by the most prominent Soviet helicopter designers as represented by the team headed by Tishchenko – the actual weights of the components are also given for several in-production Soviet helicopters. Taking advantage of this information, it is possible to conduct a more comparative analysis of the weight aspects of the major helicopter components on a higher level than of the design concepts, and producibility and maintainability. Consequently, the bulk of this volume will be devoted to weight aspects, and only a limited evaluation will be afforded to the other items.

1.2 Comparison of Weight Prediction Methods

Soviet Formulae. As mentioned in the preceding section, one can find all the formulae necessary for the prediction of the weights in Ref. 1. These formulae are summarized in Table 1.1-T, which was reproduced from Ref. 1, and then individually evaluated in Ch. 2.

Western Formulae. With respect to selecting Western counterparts for Soviet formulae, one must take into consideration that almost every major American and European helicopter company as well as most government agencies have their own preferred weight-prediction methods, some of which are considered proprietary. In view of this, it was decided to use two sets of weight-prediction formulae; one of which is represented by the method used by Boeing Vertol (Table 1.1-BV), and the other that used by the Research and Technology Laboratories (RTL) of the U.S. Army Aviation R&D Command (Table 1.1-RTL).

TABLE 1.1-T

SUMMARY OF SOVIET WEIGHT FORMULAE

HELICOPTER COMPONENT	WEIGHT FORMULAE (at $V_t = 220 m/s = 721.82 fps$)
1. MAIN ROTOR BLADES	$n_{bl} W_{bl} = k^*_{bl} (\sigma R^{2.7} / \bar{\lambda}^{0.7}) [1 + \alpha_\lambda \bar{R} (\lambda - \lambda_c)]$
2. MAIN ROTOR HUB AND HINGES	$W_h = k^*_h k_{n_{bl}} n_{bl} (CF_{bl})^{1.35}$
3. TAIL ROTOR GROUP:	
a. Tail Rotor Blades	$n_{bl_{tr}} W_{bl_{tr}} = k^*_{bl_{tr}} [\sigma_{tr} R_{tr}^{2.7} / (\bar{\lambda}_{tr})^{0.7}]$
b. Tail Rotor Hub	$W_{h_{tr}} = k^*_{h_{tr}} n_{bl_{tr}} [1 + 0.05(n_{bl_{tr}} - 4)] (CF_{bl_{tr}})^{1.35}$
4. FUSELAGE (with cowlings)	$W_f = k^*_f W_{gr}^{0.25} S_f^{0.88} L^{0.16(1 + a)}$
5. LANDING GEAR	$W_{lg} = k_{lg} W_{gr}$
6. DRIVE SYSTEM	
a. Main Gearboxes (W/attachment & lubricant)	$W_{mgb} = k^*_{mgb} n_{mgb} (\alpha_Q M_{ev})^{0.8}$
b. Angular Intermediate Gearboxes (W/lubricant)	$W_{igb} = k^*_{igb} n_{igb} (\alpha_Q M_{eq})^{0.8}$
	For twin-rotor helicopters:
	$M_{eq} = 716.2 (SHP_{tot} / n_{sh} (rpm)_{sh} \alpha)$
	For single-rotor helicopters:
	$M_{eq} = 716.2 (HP_{tr} / (rpm)_{sh})$
c. Tail-Rotor Gearbox (W/lubricant)	$W_{trgb} = k^*_{trgb} M_{tr}^{0.8}$
	where
	$M_{tr} = 716.2 (HP_{tr} / rpm_{tr})$
d. Transmission Shaft	$W_{sh} = k_{sh} L_{sh} (M_{ult})^{2/3}$

TABLE 1.1-T (Cont'd)

7. FUEL SYSTEM	$W_{fs} = k_{fs}(W_{fu})_{tot}$
8. PROPULSION SUBSYSTEMS (with engine mount, cooling system, lubricant, lubrication system, and fire suppression system	$W_{pss} = k_{pss}(SHP_{ref})_{tot}$
9. FLIGHT CONTROL GROUP a. Boosted Controls (swashplate, controls from boosters, hydraulic system of lifting rotors) b. Manual Controls (incl. auxiliary boosts)	$W_{bc} = k_{bc} n_{bl} c^2$ For twin-rotor configuration: $W_{mc} = k_{mc} L$ Fcr single-rotor configuration: $W_{mc} = k_{mc} R$

TABLE 1.1-BV

SUMMARY OF BOEING-VERTOL WEIGHT FORMULAE

HELICOPTER COMPONENT	WEIGHT FORMULA
1. MAIN ROTOR BLADES	$n_{bl} W_{bl} = 44a\left[(10^{-4} W_{gr}) n_{ff} (0.01R^2)\ 0.1(R - r)\, n_{bl}\, c k_r\ (R^{1.6}/k_d t)\right]^{0.438}$
2. MAIN ROTOR HUB AND HINGES	$W_h = 61a\left[W_{bl} R (rpm)^2_{mr} (HP_{mr}) r^{1.82}\, n_{bl}^{2.5}\, k_{mad}\, 10^{-11}\right]^{0.358}$
3. TAIL ROTOR GROUP	$W_{tr} = 14.2a\left[r_{tr}^{0.25} (0.01\, HP_{tr})^{0.5}\ 0.01\, V_{t_{tr}}\, 0.1 R_{tr}\, n_{bl_{tr}}\, c_{tr}\right]^{0.67}$
4. FUSELAGE:	
a. Body Group (incl. vertical & ventral tails)	$W_{bg} = 125a\left\{\left[(10^{-4} W_{gr}) n_{ult} (10^{-3} S_f)(L_c + L_{rw} + \Delta CG)\right]^{0.5} \log V_{max}\right\}^{0.8}$
b. Horizontal Tail	$W_{ht} = S_{ht} (sw)_{ht}$
c. Engine Mounts	$W_{em} = n_{eng} (W_{eng}\, n_{clf})^{0.41}$
d. Engine Nacelle Structure	$W_n = n_{eng}\, S_n\, k_n$
e. Air Induction	$W_{ai} = n_{eng}\, D_{eng}\, L_{ad}\, k_{ai}$
5. LANDING GEAR	$W_{lg} = k_{lg} W_{gr}$
6. DRIVE SYSTEM:	
a. Primary and Auxiliary	$(W_{ds})_{mr} = 250a_{mr}\left[(HP_{mr}/rpm_{mr})\, z_{mr}^{0.25}\, k_t\right]^{0.67}$
b. Tail Rotor	$(W_{ds})_{tr} = 300a_{tr}\left[1.1(HP_{tr}/rpm_{tr})\right]^{0.8}$
7. FUEL SYSTEM	$W_{fs} = k_{fs} W_{fu}$

TABLE 1.1-BV (Cont'd)

8. PROPULSION SUBSYSTEMS a. Engine Exhaust System b. Engine Cooling c. Engine Controls d. Engine Starting e. Engine Lubrication	$W_{pss} = k_{pss}(n_{eng} W_{eng})$
9. FLIGHT CONTROL GROUP	$W_{fc} = k_{cc}(W_{gr_{des}} 10^{-3})^{0.41} + k_{mrc}[c(R\, n_{bl} W_{bl} 10^{-3})^{0.5}]^{1.11} + k_{rsc}(W_{pmr} 10^{-3})^{0.84}$

TABLE 1.1 RTL

SUMMARY OF RTL WEIGHT FORMULAE

HELICOPTER COMPONENT	WEIGHT FORMULA
1. MAIN ROTOR BLADES	$n_{bl} W_{bl} = 0.02638\, n_{bl}^{0.6826}\, c^{0.9952}\, R^{1.3507}\, V_t^{0.6563}\, \nu_1^{2.5231}$
2. MAIN ROTOR HUB AND HINGES	$W_h = 0.002116\, n_{bl}^{0.2965}\, R^{1.5717}\, V_t^{0.5217}\, \nu_1^{1.9550} (n_{bl} W_{bl})^{0.5292}$
3. TAIL ROTOR GROUP	$W_{tr} = 1.3778\, R_{tr}^{0.0897} (HP_{mr} R_{mr}/V_{t_{mr}})^{0.8951}$
4. FUSELAGE	
a. Horizontal Tail	$W_{ht} = 0.7176\, S_{ht}^{1.1881}\, AR_{ht}^{0.3173}$
b. Vertical Tail	$W_{vt} = 1.0460\, S_{vt}^{0.9441}\, AR_{vt}^{0.5332}\, n_{gtr}^{0.7058}$
c. Fuselage Body Group	$W_{bg} = 10.13 (10^{-3} W_{gr_{max}})^{0.5718}\, n_{ult}^{0.2238}\, L^{0.5558}\, S_f^{0.1534}\, I_{ramp}^{0.5242}$
d. Cowling	$W_c = 0.2315\, S_{nw}^{1.3476}$
e. Nacelle (less cowling)	$W_{n-c} = 0.0412\, W_{eng}^{1.1433}\, n_{eng}^{1.3762}$
5A. LANDING GEAR WHEEL	$W_{lg_w} = 36.76 (W_{gr_{max}}/1000)^{0.719}\, n_{wl}^{0.4626}\, I_{rlg}^{0.0773}$
5B. LANDING GEAR SKID	$W_{lg_s} = 6.894 (W_{gr_{max}}/1000)^{1.0532}\, n_{zl}^{0.3704}\, I_{sip}^{0.1484}$
6. DRIVE SYSTEM	
a. Gearboxes	$W_{gb} = 172.7\, T_{mr_{gb}}^{0.7693}\, T_{tr_{gb}}^{0.079}\, n_{gb}^{0.1406}$
b. Drive-Shafts	$W_{dsh} = 1.152\, T_{mr_{gb}}^{0.4265}\, T_{tr_{gb}}^{0.0709}\, L_{dr}^{0.8829}\, n_{dsh}$
7. FUEL SYSTEM	
a. Fuel Tanks	$W_{ft} = 0.4341\, G_t^{0.7717}\, n_{ft}^{0.5897}\, F_{cr}^{0.393}\, F_{bs}^{1.9491}$
b. Fuel System (less tanks)	$W_{fs-t} = C_1 + C_2 (0.01\, n_{ft} + 0.06\, n_{eng}) FF_{max}^{0.866}$

TABLE 1.1-RTL (Cont'd)

8. PROPULSION SUBSYSTEMS	$W_{pss} = 2.0088\, W_{eng}^{0.5979}\, n_{eng}^{0.7858} (F_{lo})^{0.5655}$
9. FLIGHT CONTROL GROUP	
a. Cockpit Controls	$W_{cc} = 0.0985 (F_{cp})^{0.3368} (W_{gr})_{max}^{0.7452} / (F_{cb})^{1.1125}$
b. Rotating and Nonrotating Flight Controls	$W_{rfc} = 0.1657 (F_{cb})^{1.3696}\, c^{0.4981} (F_{cp})^{0.4469} (W_{gr})_{max}^{0.6865}$

NOTES RE THE ABOVE TABLE:

ITEM 4.c Presence of ramp: YES – $I_{ramp} = 2.0$; NO – $I_{ramp} = 1.0$

5A Gear retraction: YES – $I_{rlg} = 2.0$; NO – $I_{rlg} = 2.0$

5B Stiff inplane rotors: $I_{sip} = 1.0$; Soft – $I_{sip} = 2.0$

6.a $T_{mrgb} \cong HP_{trr_{mr}}/rpm_{mr}$; $T_{trgb} \equiv 100(HP_{trr_{tr}}/rpm_{tr})$

7.b Constants reflecting design features and crashworthiness – $C_1 \geq 0$; $C_2 \geq 1.0$

8. Lube oil system integral with engine – $F_{lo} = 1.0$; External – $F_{lo} = 2.0$

9. Mechanically operated – $F_{cb} = 1.0$; boosted – $F_{cb} = 2.0$

No ballistic tolerance – $F_{cp} = 1.0$; ballistic tolerance – $F_{cp} = 2.0$.

This selection was based on the fact that the Boeing Vertol formulae are summarized in HESCOMP[2] and have been discussed in various publications (e.g., Refs. 3 and 4).

The familiarity of the coauthor of this report with the RTL approach prompted the selection of this method. It should be noted at this point that the weight equations summarized in Table 1.1-RTL represent the current stage of evolution of the RTL formulae. These evolutionary changes become more visible when one compares the weight-prediction expressions given for main-rotor blades in Ref. 5 and for all the major components given in Ref. 6, with the corresponding formulae in Table 1.1-RTL.

Examination of Weight Formulae. The weight-determination formulae given by the three selected weight-prediction methods are examined and compared in Ch. 2 for each of the following major helicopter components: (1) main-rotor blades, (2) main-rotor hubs, (3) tail-rotor group, (4) fuselage, (5) landing gear, (6) drive system, (7) fuel system, (8) propulsion subsystems, and (9) flight control group.

The following weight items represent components usually provided to the design team by outside suppliers and therefore are not included in this comparison: engines, SAS, APU, instruments group, hydraulic and pneumatic group, electrical equipment, avionics equipment, furnishings and equipment, air-conditioning and anti-icing equipment, and load handling equipment.

Three pairs of actual helicopters – one Soviet and one Western in each pair – were selected from the three gross-weight classes (up to 12,000 lb, 12,000 to 30,000 lb, and 30,000 to 100,000 lb) considered in Part I. It is obvious that the make-up of these pairs should be governed by the availability of actual weight data for the major components of the compared helicopters. Once the actual weights of the components were available, the accuracy of the various methods predicting those weights could be evaluated.

In this process, the actual formulae as well as the numerical values of the various parameters appearing in the formulae are shown in the appropriate tables in Ch. 2. Once this is done for all nine of the major helicopter components, the necessary basis for a comparison of the weight-prediction methods is established. It is obvious that a necessary condition for making a valid comparison is the availability of reliable data on the actual component weights.

Actual Weight Data. With respect to Western helicopters, the desired actual data for several of the helicopters considered in Part I could be obtained from available weight statements. Fortunately, the necessary information was also available, again from Ref. 1, for the most important Soviet representatives of the three gross-weight classes examined in Part 1; namely, the Mi-2, Mi-8, and Mi-6. The following component weights were obtained from the tables[1] cited below.

Main Rotor Blades	Table 2.1
Main Rotor Hubs	Table 2.1
Main Rotor Gearboxes	Table 2.2(a)
Intermediate Gearboxes	Table 2.2(b)
Shafts	Table 2.2(b)
Tail-Rotor Blades	Table 2.4
Tail-Rotor Hubs	Table 2.4
Fuselages	Table 2.5

The calculations of the weights of the other major components given in the Appendix to Ch. 2 were based on weight-coefficient values given in various graphs of Ref. 1 for the considered helicopters.

Boosted Controls and Swashplates	Fig. 2.10
Powerplant Installation	Fig. 2.31
Fuel System	Fig. 2.32
Landing Gears	Fig. 2.42

1.3 Selection of Helicopters for Comparison

Pairs of Actual Soviet and Western Helicopters. As mentioned in the preceding section, weight data for major components were available for the Mi-2, Mi-8, and Mi-6 helicopters. Since, in addition, each of them is the most important Soviet representation of its weight class, they were a logical choice to represent Soviet designs in the considered helicopter pairs. With respect to the selection of their Western counterparts, it was decided to use the BO-105, YUH-61A, and CH-53E, as the actual component weights of these helicopters were available. Thus, the following pairs of actual helicopters in each gross-weight class were formed:

up to 12,000-lb GW Class

Mi-2 – BO-105

12,000 to 30,000-lb GW Class

Mi-8 – YUH-61A

30,000 to 100,000-lb GW Class

Mi-6 – CH-53E

Soviet Hypothetical Helicopters. It was also stated in Part I that Soviet hypothetical helicopters should be of special interest in a comparative study as they are probably indicative of future design trends. It was also clear from the general design comparison that the Soviets realize that significant improvements can be made in their current rotorcraft, especially in the structural weight areas.

The information on the weights of the major components of the 15 and 52 metric-ton gross-weight helicopters is the most complete of all the hypothetical helicopters considered in Ref. 1. The necessary data for the 15 metric-ton helicopter can be taken directly from Table 2.8[1], and can be ascertained for the 52 metric-ton machine from Figs. 2.79, 2.82, and 2.85. Consequently, relative weights of some of the major components and specific weights of the drive system for the 15 and 52 metric-ton gross-weight single-rotor and tandem hypothetical configurations along with those of actual Soviet and Western helicopters are shown in Ch. 3.

It is believed that the above-outlined procedure should provide an insight into the various component weight aspects of Soviet helicopters.

1.4 Evaluation of Component Design Aspects

General Remarks. Comparisons of helicopters as a whole are usually conducted on the basis of their flight performance, overall weight aspects, vibration levels, and many other characteristics that are, as a rule, expressed in figures available to the evaluator.

But when it comes to a comparison of the design aspects of major components, one can usually find only general descriptions and a few figures; leaving many factors undefined in their magnitude of importance. Consequently, the design comparison of Soviet vs. Western major helicopter components will, of necessity, be limited to the three areas considered in Ch. 3: (a) relative weights, (b) maintainability, and (c) overall evaluation of the component design.

Relative Weight Comparisons. The comparison of relative weights will be made for the nine major helicopter components considered in Ch. 2. The relative weights of these components will be calculated and graphically presented as ratios of the actual component weight to both design and maximum flying gross weights. This will be done for all three pairs of Soviet–Western helicopters considered in Ch. 2. However, in order to obtain some insight into the relative weight aspects of the tandem, inputs related to the CH-47D and XCH-52A will be added. Furthermore, relative component weights for the Soviet 15 and 52 metric-ton single-rotor, tandem, and side-by-side hypothetical helicopters will also be included in order to gain some insight into current and future Soviet design trends.

Maintainability. Because the available maintainability data regarding Soviet helicopters were limited to the Mi-2, a direct comparison was restricted to the comparison of the Mi-2 with the BO-105, SA330J, and the Boeing Vertol 107 and CH-47D. This comparison was supplemented with an analysis of Soviet design trends regarding maintenance, as evidenced in Ref. 1, and reports and discussions with Eastern experts on helicopter blades.

Merit Evaluation of the Overall Component Designs. It would be desirable to develop a method of evaluating various design features of components and to present them in numerical form, thus permitting one to rate the various components of the compared helicopters on a quantitative basis.

There are obviously many possible ways of achieving this goal. The one attempted in this study consists of identifying various design features of a major component and assigning "merit points" wherein the total would provide a guage for assessing the excellence of the design according to accepted criteria.

Nine assemblies have been identified as major helicopter components for weight considerations. A thorough evaluation and ranking of each component for the twenty-three existing helicopters and the hypothetical helicopters considered in Part I would carry this study beyond its intended size. Consequently, it was decided to concentrate on the most vital 'ingredient' of any helicopter – namely, the rotor system as represented by the blade-hub assembly, and to limit the number of helicopters to the three pairs shown on page 9.

The Index-of-Merit Tables were developed and the overall design excellence of the blades and hubs were numerically evaluated with the help of these tables.

1.5 Rating of Helicopter Configurations by Tishchenko, et al

On the basis of payload-carrying capabilities over short (50 km) and long (800 km) flight distances, Tishchenko et al[1] rated large transport helicopter configurations (40 to 60 m.ton gross-weight class) in the following order: first, single rotors; second side-by-side; and third, tandems.

Verification or discredit of the above ranking could be obtained through an independent sizing study such as the HESCOMP technique[2]. However, it is believed that an approximate solution can be obtained more simply by indicating that the relative-weight trends of the major helicopter components represent first-order inputs regarding the payload-carrying capabilities of the compared configurations, and then comparing the relative weight trends assumed by Tishchenko with those demonstrated by actual single-rotor and tandem helicopters developed in the West. Side-by-side large transport machines however, must be excluded from the verification as there has been no design experience with that configuration outside of the USSR.

An abbreviated analysis of the configuration rating is performed at the conclusion of this study.

Chapter 2

Comparison of Weight–Prediction Methods

2.1 Introduction

The rationale for the selection of three representative weight-prediction methods for three gross-weight categories of Soviet and Western helicopters was given in the preceding chapter. We will now establish a criterion for a comparison of the three methods by alternatively applying each method to weight estimates of the nine basic components of each of the three selected pairs of helicopters. The formulae best suited for preliminary design and concept formulation stages are briefly discussed, and the outlying philosophy in their formulation are indicated. Then, tables containing values (either known or assumed) of all the parameters appearing in the considered formulae are listed. This provides a basis for determining the computed component weight which is shown side-by-side with the actual weight of the component. The ratios of the predicted weights to actual weights are also shown. These latter values are also presented in graphical form, thus permitting one to see at a glance how closely each of the three compared weight-prediction methods comes to forecasting actual component weights.

Since only actual helicopters are considered in this comparison, much information regarding design details of the major components is available. Although knowledge of these details might contribute to more accurate weight predictions, no advantage of this additional information will be taken here, as it would not be obtainable in the concept formulation and preliminary design stages. Consequently, in order to make the whole comparative component weight prediction study as realistic as possible from the point of view of their applicability to the early design phases, only inputs that would be known at that stage are used here.

2.2 Main-Rotor Blades

<u>Tishchenko's Formulae.</u> Chapter 3 of Reference 1 is devoted to the method of weight-predictions of blades, especially those of steel and extruded-aluminum spar designs. However, for preliminary-design and concept-formulation stages, the following weight formula is given for weight estimates of all main-rotor blades.

$$n_{bl} W_{bl} = k^*_{bl}(\sigma R^{2.7}/\bar{\lambda}^{0.7})[1 + \alpha_\lambda \bar{R}(\lambda - \lambda_o)] \tag{2.1}$$

In the above equation, it can be seen that only parameters representing geometric characteristics of the rotor as a whole (solidity ratio σ and blade radius R) plus the aspect ratio of the blade itself (λ) are taken into consideration. Here, the blade aspect ratio is defined as $\lambda \equiv R/c_{0.7}$, $\bar{\lambda} \equiv \lambda/18$, and $\lambda_o \equiv 20/\bar{R}$ for steel-tube, and $\lambda_o \equiv 12.4/\bar{R}$ for extruded-aluminum spar blades, while $\bar{R} \equiv R/16$, where R is in meters. The suggested values of α_λ are 0.015 for steel-tube, and 0.011 for extruded-aluminum spar blades.

For $\lambda < \lambda_o$, the expression in the square brackets of Eq (2.1) is arbitrarily taken as one. Consequently, only when $\lambda - \lambda_o > 0$ does the type of blade design (limited here to steel-tube vs. extruded-aluminum spar) enter the weight-prediction picture. Otherwise, there is no consideration of such important design features as type of rotor (hingeless, teetering, or articulated) and such aspects as thrust and power, or torque, per rotor and tip speeds.

It may be expected hence, that for an established type of blade design where the only changes are of a dimensional nature, Eq (2.1) may predict correct trends. However, for new designs, the selection of a proper value of the blade-weight coefficient k^*_{bl} becomes the most important decision regarding the weight estimate of the assembly.

Unfortunately, a glance at Fig. 2.1 (Fig. 2.2 of Ref. 1) indicates that there is a considerable scatter of the k^*_{bl} values when plotted vs. R (computed here with no consideration of the differences in blade aspect ratios). Furthermore, there appears to be a definite trend (as indicated by the dashed line marked on Fig. 2.1 by these authors) toward a considerable increase in the k^*_{bl} level as the blade radius decreases. This trend appears to be further supported by Fig. 2.2 (Fig 3.20 of Ref. 1) where the influence of both blade radius and chord were examined, at least for the steel-tube and extruded-aluminum spar blades.

However, for such large diameter blades as may be anticipated in transpo[illegible]copters, the differences in k^*_{bl} values appear to diminish. This provides a rationale for th[illegible] the single k^*_{bl} = 13.8 kg/m$^{2.7}$ value for estimating blade weights of the hypothetica[illegible]oters in Table 2.10[1]. Consequently, in Table 2.1-T (T representing Tishchenko), a cons[illegible] of k^*_{bl} = 13.8 kg/m$^{2.7}$ was first assumed in the estimates of all the considered blade weights. As expected, this assumption led to weight underpredictions of the small-radius rotor blades. This is especially visible in

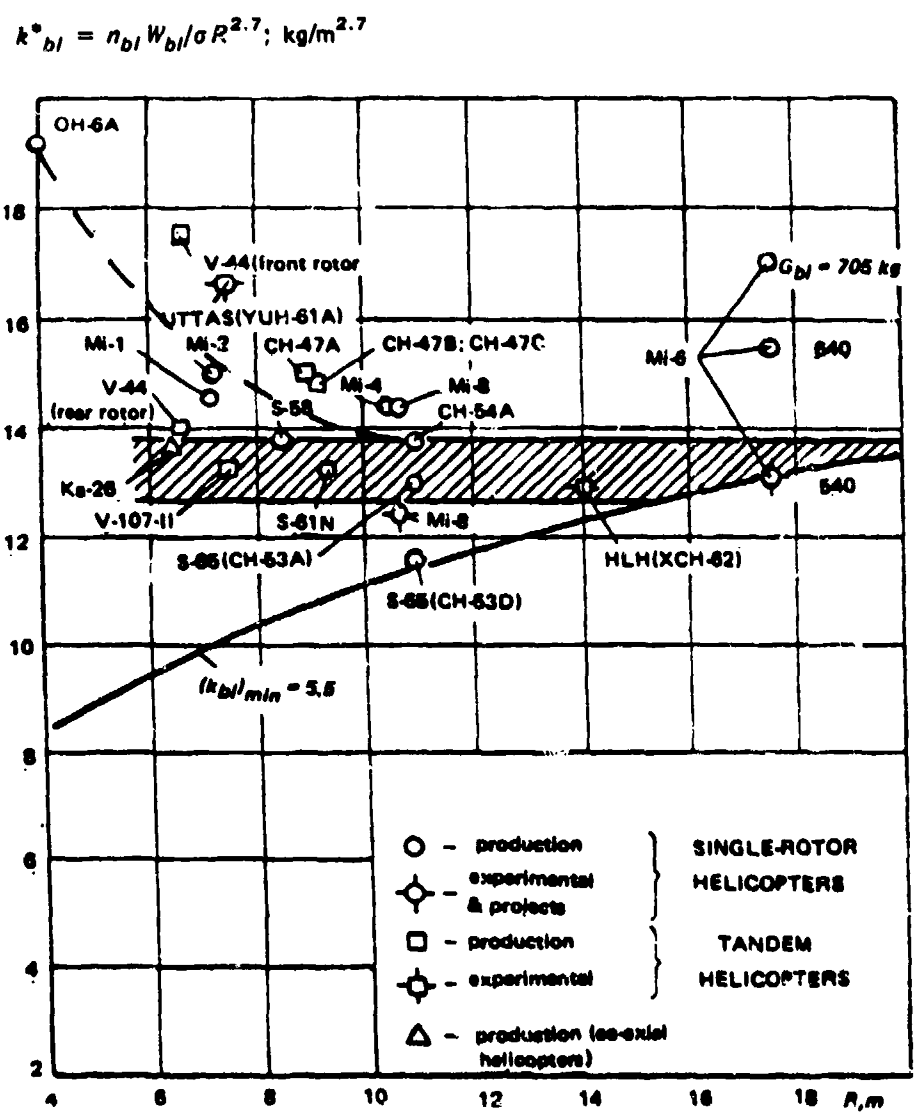


Figure 2.1 Lifting-rotor blade weight coefficient, k^*_{bl}, with no consideration of differences in blade aspect ratios (hatched area corresponds to the best blades, from a weight point-of-veiw, for large scale operations).

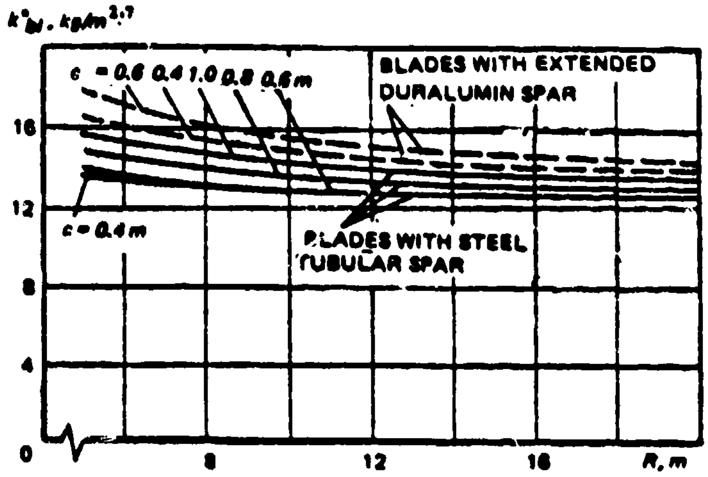


Figure 2.2 Variation of weight coefficient k^*_{bl} for the considered blade types throughout the range of examined values of c and R: — — — blade with extruded Duralumin spar; and ——— blade with tubular steel spar.

the case of the BO-105 where the so-predicted blade weight amounts to only 57 percent of the actual one.

Assumption of the k^*_{b} values along the dashed line in Fig. 2.1 (k^*_{bl} = 17.5) would lead to a more accurate blade weight prediction for the BO-105 of $n_b W_{bl}$ = 194.4 lb, and the resulting ratio of the predicted to the actual blade weight of 0.71—somewhat better than before, but still not very accurate.

It may be anticipated that in this case, taking corrections associated with a small blade radius is not enough. The type of the design—represented by the hingeless rotor configuration—might lead to a discrepancy.

In order to further investigate this problem, the blade weight of another hingeless configuration, as represented by the YUH-61A, were computed from Eq. (2.1); first using k^*_{bl} = 13.8, and then 15.0 kg/m$^{2.7}$ (dashed line value from Fig. 2.1). In the first case, the predicted weight amounted to 878.3 lb vs. the actual weight of 1013 lb; thus leading to the predicted to actual weight ratio of 0.87. At the higher value of the blade-weight coefficient (k^*_{bl} = 15.0), this ratio improves, becoming equal to 0.94.

However, this additional example of the YUH-61A blades (especially with k^*_{bl} = 13.8) tends to confirm the original statement that Eq (2.1) would underpredict the blade weights of hingeless rotors.

Further investigation of Table 2.1-T indicates that Eq. (2.1) with k^*_{bl} = 13.8 would probably overestimate the weights of the large modern articulated blades with titanium spar and fiber/epoxy composite material skin as in the case of the CH-53E.

Boeing-Vertol Formula. As can be seen from Eq (2.2)[3], the basic philosophy of the main-rotor, blade-weight prediction method of Boeing Vertol is quite different from that of Tishchenko:

TABLE 2.1-T

MAIN-ROTOR BLADE WEIGHT ESTIMATES
FOR THREE HELICOPTER PAIRS

ITEM	HELICOPTER					
	UP TO 12,000 LB		12,000 TO 30,000 LB		30,000 TO 100,000 LB	
	Mi-2	BO-105	Mi-8	UH-60A	Mi-6	CH-53E
ACTUAL WEIGHT, LB	363.8	268.2	1278.9/1477.4†	841.1	5953.5/7772.6	2884.9
TISHCHENKO WEIGHT FORMULA	$n_{bl} W_{bl} = k^*_{bl}(\sigma R^{2.7}/\bar{\lambda}^{0.7})[1 + \alpha_\lambda \bar{R}(\lambda - \lambda_o)]$					
PARAMETER	VALUES					
n_{bl}	3	4	5	4	5	7
k^*_{bl}; kg/m$^{2.7}$	13.8/15.2	13.8/17.5	13.8	13.8/15.0	13.8	13.8
σ	0.0625	0.0702	0.0777	0.0821	0.0909	0.1398
R; m	7.25	4.92	10.65	8.18	17.50	12.04
$\bar{\lambda} \equiv \lambda/18$	1.01	1.01	1.14	0.82	0.97	0.892
α_λ	0.011	[0.015]	0.011	[0.015]	0.015	[0.015]
$\bar{R} \equiv R/16$	0.453	0.307	0.666	0.511	1.094	0.752
$\lambda \equiv R/c$	18.12	18.13	20.48	14.83	17.5	16.06
(a) $\lambda_o \equiv 20/R$ or (b) $12.4/R$	27.37	[65.04]	18.62	[39.12]	18.28	[26.60]
$(\sigma R^{2.7}/\bar{\lambda}^{0.7})[1 + \alpha_\lambda \bar{R}(\lambda - \lambda_o)]$	10.97	5.15	42.66	27.49	217.45	124.4
COMPUTED WEIGHT, kg	151.39/166.7	69.52/90.1	588.7	379.3/412.3	2910.0	1716.8
COMPUTED WEIGHT, lb	333.8/367.6	153.3/198	1298.1	836.4/909.1	6416.8	3785.5
PREDICTED TO ACTUAL WEIGHT RATIO	0.92/1.0	0.57/0.74	1.02/0.88	0.99/1.08	1.08/0.8[illegible]	1.31

Notes: † Glass fibre/extruded aluminum spar
(a) steel-spar blades (also assumed for titanium spar and all fiberglass blades)
(b) extruded-aluminum spar blades

$$n_{bl}\,W_{bl} = 44a\,[(10^{-4}\,W_{gr}n_{lf})(0.01R^2)0.1(R-r)n_{bl}ck_r(R^{1.6}/k_dt)]^{0.438} \qquad (2.2)$$

Although Eqs (2.1) and (2.2) both contain parameters reflecting rotor and blade geometry, the quantities in Eq (2.2) are more detailed since, in addition to the rotor radius R, explicit parameters are given for the radius of the blade attachment (r), blade chord (c), and number of blades; while in Eq (2.1), the number of blades and blade chord are implied through rotor solidity.

Eq (2.2) also contains parameters reflecting the maximum load carried by the rotor ($W_{gr}n_{lf}$, where n_{lf} is the design maneuver load factor) and the k_r coefficient, depending on the rotor type (i.e., k_r = 1.00 for articulated rotors, and k_r = 2.2 for hingeless or teetering configurations).

Both equations contain a term reflecting droop conditions. In Eq (2.2) this term is expressed as $(R^{1.6}/k_dt)$, where the droop constant k_d = 1000 for tandem, and 1200 for single-rotor configurations, and t is the blade thickness in feet at $r = 0.25R$. As in the preceding case, the droop term is used if its value is greater than 1.0.

An acceptable statistical correlation of predicted and actual blade-weight values is obtained (Fig. 2.3) through selection of the exponent value of the expression in the square brackets (0.438) and the fixed coefficient in front of the brackets (44.0).

Deviations of the a coefficient in Eq (2.2) from a = 1.0 to a = 0.8, and a = 1.2 indicate the scatter limits. However, a = 1.0 was assumed for the calculations shown in Table 2.1-BV (BV representing Boeing Vertol).

__RTL Formula.__ The RTL weight formula is as follows:

$$n_{bl}\,W_{bl} = 0.02638n_{bl}^{0.6826}\,c^{0.9952}\,R^{1.3507}\,V_t^{0.6563}\,\nu_1^{2.5231} \qquad (2.3)$$

In this equation, there are three parameters (n_{bl}, c, and R) reflecting the overall geometry of the rotor. Two new parameters, not appearing in the Tishchenko and Boeing Vertol formulae, are also present: tip speed (V_t) and the first natural blade frequency in flap-bending (ν_1).

The selection of the values of the constant coefficient and exponent associated with each parameter is the principal means for obtaining the best possible statistical correlation between the predicted and actual blade weights assembled as test cases.

Similar to Eq (2.2), a term reflecting the type of rotor design also appears in Eq (2.3). However, instead of the coefficient k_r (having a value of 1.0 for articulated rotors and 2.2 for hingeless rotors) appearing in Eq (2.2), the term ν_1 to the relatively high power of 2.5231 is used in Eq (2.3).

In conjunction with both approaches, it may be of interest to compare the weight ratios of two almost identical blades; the exception being that one is of the hingeless, and the other of the articulated type. According to Eq (2.2), this ratio would be $2.2^{0.438} \approx 1.41$. However, using typical ν_1 values of 1.12 for the hingeless type, and 1.03 for articulated rotors, the blade weight ratio would be $(1.12/1.03)^{2.5231} = 1.24$ – considerably lower than predicted by the Boeing Vertol formula. On the other

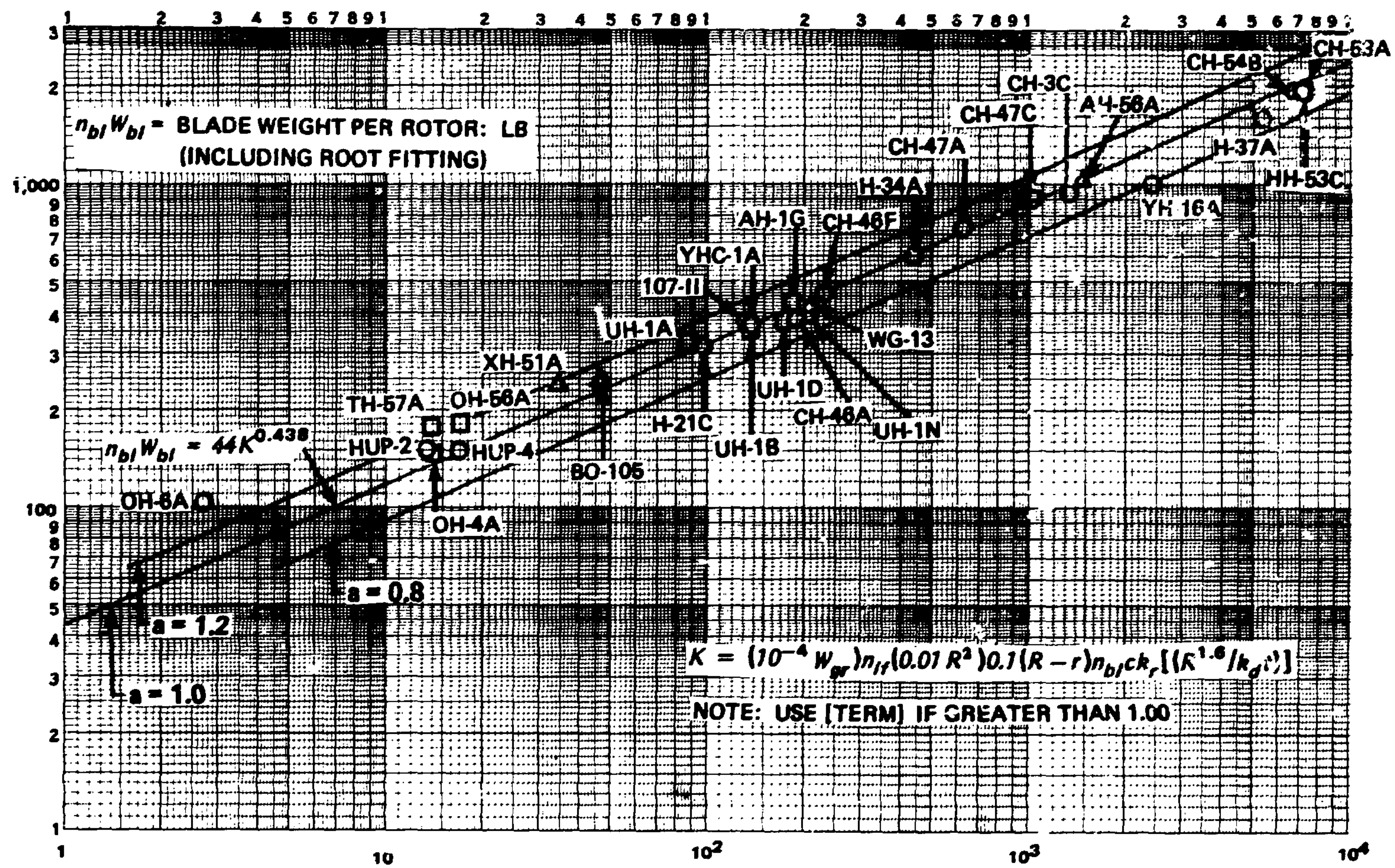


Figure 2.3 Rotor blade weight trend

TABLE 2.1-BV

MAIN-ROTOR BLADE WEIGHT ESTIMATES
FOR THREE HELICOPTER PAIRS

ITEM	HELICOPTER					
	UP TO 12,000 LB		12,000 TO 30,000 LB		30,000 TO 100,000 LB	
	Mi-2	BO-105	Mi-8	UH-60A	Mi-6	CH-53E
ACTUAL WEIGHT, LB	363.8	268.2	1278.9/1477.4	841.1	5953.5/7772.6	2884.9
BOEING VERTOL WEIGHT FORMULA	$n_{bl}W_{bl} = 44a\,[(10^{-4}W_{gr}n_{lf}(0.01R^2)0.1(R-r)n_{bl}ck_r(R^{1.6}/k_d t))]^{0.438}$					
PARAMETER	VALUES					
a	1.0	1.0	1.0	1.0	1.0	1.0
W_{gr}; lb	8158	4442	24,255	16,835	90,405	56,000
n_{lf}; g's	[2.75]	3.5	[2.75]	3.5	[2.75]	3.0
R; ft	23.88	16.14	34.94	26.83	57.42	39.50
r; ft	[1.09]	1.22	[2.19]	2.50	[4.10]	4.73
n_{bl}	3	4	5	4	5	7
c; ft	1.312	0.89	1.71	1.73	3.28	2.44
k_r	1.0	2.2	1.0	1.0	1.0	1.0
k_d	1200	1200	1200	1200	1200	1200
t; ft	0.157	0.107	0.206	0.208	[0.394]	[0.293]
$R^{1.6}/k_d t$ †	0.851	0.667	1.192	0.774	1.380	1.02
COMPUTED WEIGHT, lb	352.2	238.3	1300.9	782.4	6782.3	3044.8
PREDICTED TO ACTUAL WEIGHT RATIO	0.97	0.89	1.02/0.88	0.93	1.14/0.87	1.055

NOTE: †Use if > 1.0

hand, it can be seen from Table 2.1-RTL (RTL representing the Research and Technology Labs) that Eq (2.3) predicts the weight of the BO-105 main-rotor blades much closer than Eq (2.2) if the normal design gross weight is assumed. As in the case of Eq (2.1), in order to check the validity of the RTL approach with respect to the weight estimation of hingeless rotors, that quantity was calculated for the YUH-61A helicopter and resulted in $n_{bl}W_{bl}$ = 992.4 lb vs. the actual 1013 lb; thus showing a very good ratio of W_{cal}/W_{act} = 0.98.

It can be seen from Table 2.1-RTL that main-rotor blade-weight predictions for the two other Western helicopters could be considered as good (UH-60A) or very good, as in the case of the CH-53E. With respect to Soviet designs, Eq (2.3) over-predicts the blade weight of the Mi-2 by 6 percent. However, it exactly matches the weight of the lighter blades for the Mi-8, and under-predicts the heavier blades of that machine by about 13 percent. With respect to the Mi-6, under-prediction of the heavier blades is quite considerable (about 36 percent). Even for the lighter blades, the under-prediction still amounts to about 27 percent. In the case of the Mi-6, Eq (2.2) gives better results as, for the lighter blades, it over-predicts the blade weight by about 14 percent, and for heavier ones, under-predicts their weight by approximately the same amount (13 percent).

Discussion. The three methods of main-rotor blade weight predictions represent somewhat different philosophies of relating blade weight to various parameters. However, all contain some coefficients and parameter exponents having values selected in order to obtain some agreement with statistical data representing existing blades. Consequently, when there is a radical departure, either in the blade design concepts, size, or materials from those representing the supporting statistics, differences in predicted and actual weights may be expected to be higher than for "conventional" designs.

The ratios of the predicted to the actual blade weights are summarized in Fig. 2.4. A glance at that figure would indicate that out of the three compared methods, that by Tishchenko appears to be the most erratic as far as prediction of the weights of main-rotor blades is concerned. This is especially true if a constant k^*_{bl} = 13.8 coefficient is assumed, regardless of the rotor diameter. Variation of that coefficient value along the broken line of Fig. 2.1 somewhat improves the blade-weight predictions in the cases of the BO-105 and YUH-61A, but for the UH-60A, does not contribute to an improvement in accuracy. For the large Western helicopters as represented by the CH-53E, Tishchenko over-predicts the weight of a modern titanium spar, fiberglass envelope, articulated blade by about the same percentage margin as it under-predicts those weights for a modern hingeless composite blade.

It appears, hence, that the Tishchenko method as represented by Eq (2.1) should not be considered as a reliable tool for predicting the main-rotor blade weight in the preliminary design and concept formulation phase, especially if the design of the new machine should incorporate blades deviating from the classical concepts of a fully articulated rotor with steel or extruded aluminum spar blades.

The Boeing-Vertol and RTL methods appear to be better suited for dealing with rotors of various sizes and representing diverse design concepts (e.g., hingeless vs. articulated). The RTL method shows a larger than normal discrepancy in under-predicting the weights of the Mi-6 main-rotor blades. This

TABLE 2.1-RTL

MAIN-ROTOR BLADE WEIGHT ESTIMATES
FOR THREE HELICOPTER PAIRS

ITEM	HELICOPTER					
	UP TO 12,000 LB		12,000 TO 30,000 LB		30,000 TO 100,000 LB	
	Mi-2	BO-105	Mi-8	UH-60A	Mi-6	CH-53E
ACTUAL WEIGHT, LB	363.8	268.2	1278.9/1477.4	841.1	5953.5/7772.6	2884.9
RTL WEIGHT FORMULA	$n_{bl} W_{bl} = 0.02638\, n_{bl}^{0.6826}\, c^{0.9952}\, R^{1.3507}\, V_t^{0.6563}\, \nu_1^{2.5231}$					
PARAMETER	VALUES					
n_{bl}	3	4	5	4	5	7
c; ft	1.31	0.89	1.71	1.73	3.28	2.33
R; ft	23.88	16.14	34.94	26.83	57.42	39.50
V_t, fps	615.2	716.5	702.5	725.0	721.4	740.4
ν_1	1.03	1.12	1.03	1.02	1.03	1.04
COMPUTED WEIGHT, lb	363.8	257.7	1273.6	774.3	4965.0	2926.0
PREDICTED TO ACTUAL WEIGHT RATIO	1.06	0.96	1.00/0.87	0.92	0.83/0.64	1.01

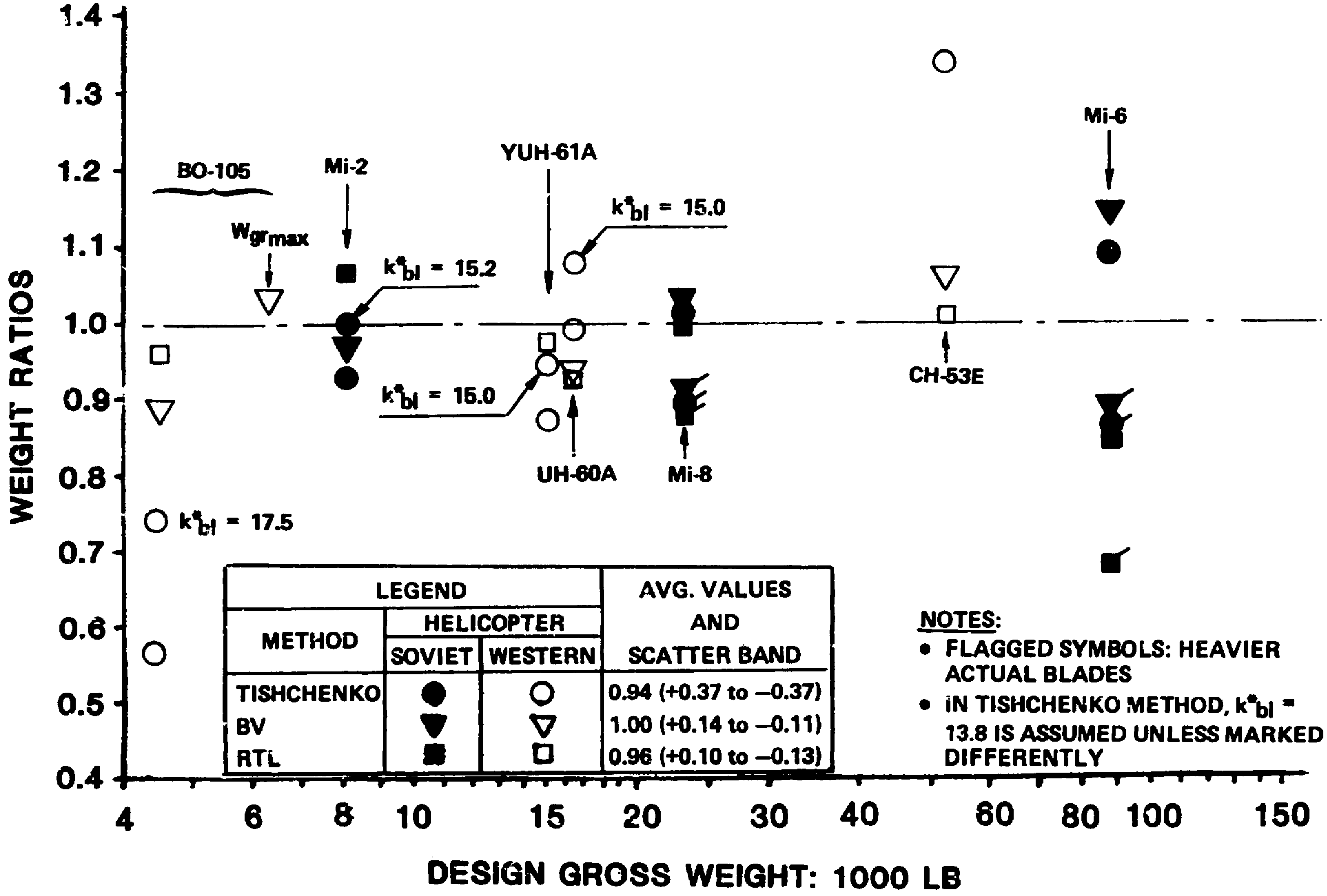


Figure 2.4 Predicted-to-actual weight ratios of main-rotor blades

discrepancy is especially noticeable for the heavier blades. It should be noted that for those two cases where the actual weights of the heavier and lighter blades are given (Mi-8 and Mi-6), both Western methods predict weights that are closer to the lighter actual weights, thus reflecting possibilities of achieving the predicted levels through more advanced designs. The previous statements regarding the accuracy of the compared methods are further supported by the average values of the predicted to actual weight ratios (based on the lighter sets of blades) and width of the scatter bands, as shown in the last column of the table in Fig. 2.4.

2.3 Main-Rotor Hubs and Hinges

Tishchenko Formula. The formula for estimating the weights of the main-rotor hub and hinges is given in Ref. 1 as

$$W_h = k^*_h k_{n_{bl}} n_{bl} (CF)^{1.35} \tag{2.4}$$

Here, the centrifugal force per blade (CF, expressed in metric tons) and number of blades (n_{bl}) are the two significant parameters, while statistical correlation with actual hub and hinge weights is achieved through the k^*_h and $k_{n_{bl}}$ coefficients. The latter of these coefficients should be considered as a correction factor indicating a weight increase when the number of blades becomes $n_{bl} > 4$. When this occurs, the $k_{n_{bl}}$ coefficient should be computed from the following:

$$k_{n_{bl}} = 1 + \xi_{n_{bl}}(n_{bl} - 4) \tag{2.5}$$

where it may be assumed that $\xi_{n_{bl}} \approx 0.05$.

It can be seen from Fig. 2.5 that in spite of the $k_{n_{bl}}$ coefficient, the k^*_h values, similar to the blade-weight coefficients in Fig. 2.1, also exhibit a considerable scatter. Furthermore, it is clear from Fig. 2.5 that the k^*_h values increase, again in analogy to the k^*_{bl} case, for smaller helicopters. However, in spite of this, a single value of $k^*_h = 1.15$ was assumed for the hypothetical helicopters (Table 2.10[1]).

Although this approach may be justified for large transport helicopters, one might expect that for smaller machines, Eq (2.4) with $k^*_h = 1.15$ should under-predict the actual hub weights. But this generalization is not completely correct, as one can see from Table 2.2-T that in the case of the BO-105, Eq (2.4) grossly over-predicts the hub weight. This is obviously due to the fact that no distinction is made of the hub type (e.g., articulated vs. hingeless rotors). Also, Eq (2.4) does not reflect the hub material. Consequently in the case of the UH-60A (Table 2.2-T), it again highly over-predicts the weight of the titanium hub, although the rotor itself is of the articulated type.

In order to check as to whether Eq (2.4) with $k^*_h = 1.15$ would over-predict weights of hingeless rotor hubs, W_h was computed for the YUH-61A helicopter, resulting in $W_h = 1565.9$ lb vs. the actual weight of 590 lb, resulting in $W_{h_{cal}}/W_{h_{act}} \approx 2.65$. This once more demonstrates that $k^*_h = 1.15$ is of little value in predicting main-rotor hub weights of hingeless rotors.

$$k^*_h = W_h/n_{bl}[1 + 0.05(n_{bl} - 4)](CF)^{1.35};\ \text{kg/ton}^{1.35}$$

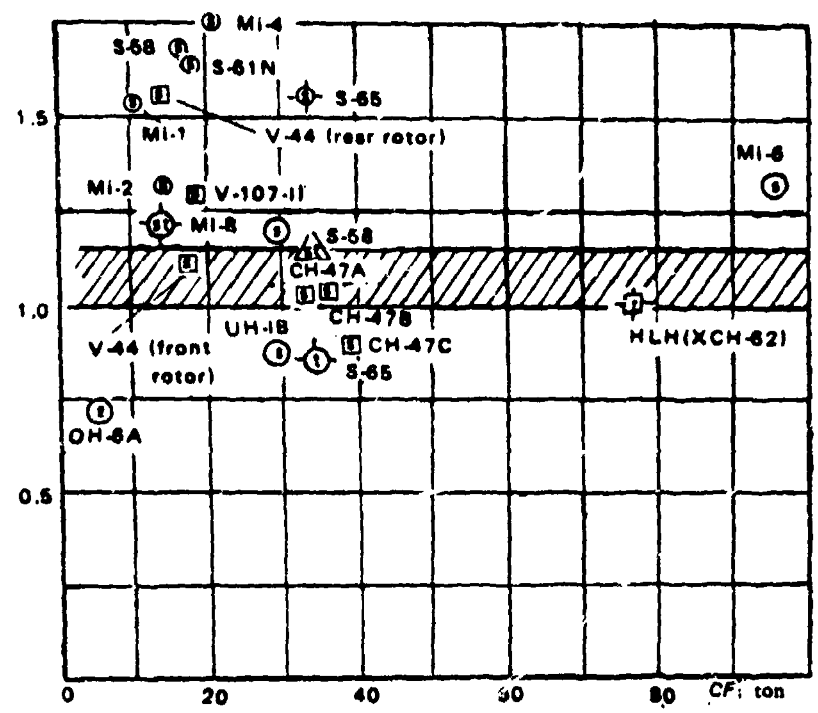


Figure 2.5 Main-rotor hub weight coefficients k^*_h

In the case of Western articulated rotors (UH-60A and CH-53E), the values of predicted hub weights are also considerably higher (57, and 22 percent, respectively) than the actual weights. It should be noted that the lower percentage difference occurring in the case of the CH-53E, as opposed to similar land-based helicopters, can be explained by the relatively heavier hub made necessary because of the automatic blade-folding requirement. Only the hub weights of the three Soviet helicopters seem to be fairly predicted by Eq (2.4), with $k^*_h = 1.15$.

TABLE 2.2-T

MAIN—ROTOR HUB WEIGHT ESTIMATES FOR THREE HELICOPTER PAIRS

ITEM	HELICOPTER					
	UP TO 12,000 LB		12,000 TO 30,000 LB		30,000 TO 100,000 LB	
	Mi-2	BO-105	Mi-8	UH-60A	Mi-6	CH-53E
ACTUAL WEIGHT, LB	291.0	200.5	1333.0	605.9	7331.6	3472.1
TISHCHENKO WEIGHT FORMULA	$W_h = k^*_h k_{n_{bl}} n_{bl} (CF_{bl})^{1.36}$					
PARAMETER	VALUES					
n_{bl};	3	4	5	4	5	7
k^*_h; kg/ton$^{1.36}$	1.15	1.15	1.15	1.15	1.15	1.15
$k_{n_{bl}}$	1.0	1.0	1.05	1.0	1.05	1.15
CF_{bl}; m.ton	13.5[1]	15.31	29.5/25.4[1]	28.97	96.0/72.5[1]	40.41
ω, rad/sec	–	44.39	–	27.02	–	18.73
W_{bl}; kg	–	31.00	–	95.17	–	187.70
R_{bl}; m	–	4.92	–	8.18	–	12.04
COMPUTED WEIGHT, kg	115.82	183.0	582.2	432.3	2863.7	1365.4
COMPUTED WEIGHT, lb	255.4	403.5	1283.9	953.2	6314.4	3010.7
PREDICTED TO ACTUAL WEIGHT RATIO	0.88	2.00	0.96	1.57	0.86	1.22

Boeing Vertol Formula. In this approach, the main-rotor hub weight is expressed as follows:

$$W_h = 61a\left[W_{bl}R_{mr}(rpm)^2_{mr}(HP_{mr})r^{1.82}n_{bl}^{2.5}k_{mad}10^{-11}\right]^{0.358} \qquad (2.6)$$

The basic rationale of this formula is explained in Ref. 3, while here only the most important features of Eq (2.6) are indicated. It should be noted that similar to Eq (2.4), the parameters in Eq (2.6) represent the contribution of the blade centrifugal force; namely, the $W_{bl}R_{mr}(rpm)^2_{mr}$ product. However, in this case, the centrifugal force term is taken to the power of 0.358, while in Eq (2.2), it was to the power of 1.35. As in Eq (2.4), Eq (2.6) also contains a term representing the number of blades, but here it is to the power of 2.5 × 0.358 = 0.895, instead of the 1.0 in Tishchenko's formula. Furthermore, in the Boeing-Vertol approach, one will find such additional parameters as takeoff horsepower per rotor (HP_{mr}), distance from the rotor axis of rotation to the blade attachment (r, in ft) and the k_{mad} factor reflecting (m) material (steel, 1.0 and titanium, 0.56), (a) design approach (articulated, 1.0 and hingeless, 0.53), and (d) development stage (early, 1.0 and developed, 0.62).

As in the case of Eq (2.2), the values of the fixed coefficient (61) and the exponent (0.358) of the expression in square brackets were selected in order to provide the best possible statistical correlation between the predicted and the actual hub weights. It can be seen from Fig. 2.6 that a very good correlation was obtained with the sample cases.

When applied to the three pairs of compared helicopters, the performance of Eq (2.6) can be judged from Table 2.2-BV. In this table, the hub weights of Western helicopters, as exemplified by the UH-60A and CH-53E, are predicted very well. In the case of the BO-105, there is a weight under-estimate of about 14 percent if a transmission-limited power of 690 hp is assumed, but this under-estimate would be reduced to about 9 percent if a rotor horsepower of 800, corresponding to the installed power, was assumed.

With respect to Soviet designs, Eq (2.6) greatly under-estimates the hub weights. For the Mi-2, this under-estimate is of the order of 36 percent, about 26 to 30 percent for the Mi-8, and reaches a level of 53 to 57 percent for the Mi-6. Here, one finds a reversal of the trend exhibited by Tishchenko's formula with respect to hub weight estimates of Western helicopters, where the weights were consistently overpredicted by Eq (2.4), with k^*_h = 1.15. This seems to indicate that the designs of Soviet main-rotor hubs (on which the value of the k^*_h coefficient was principally founded) are basically heavier than those of their Western counterparts, especially as in the case of the heavy-lift helicopter represented by the Mi-6.

RTL Formula. The RTL weight-prediction formula for hub and hinge assembly is as follows:

$$W_h = 0.002116n_{bl}^{0.2966}R^{1.6717}V_t^{0.5217}\nu_1^{1.9550}(n_{bl}W_{bl})^{0.5292} \qquad (2.7)$$

A glance at the above equation would indicate that it contains all of the parameters (R, V_t, and W_{bl}) contributing to the magnitude of the blade centrifugal force acting on the hub. The number of

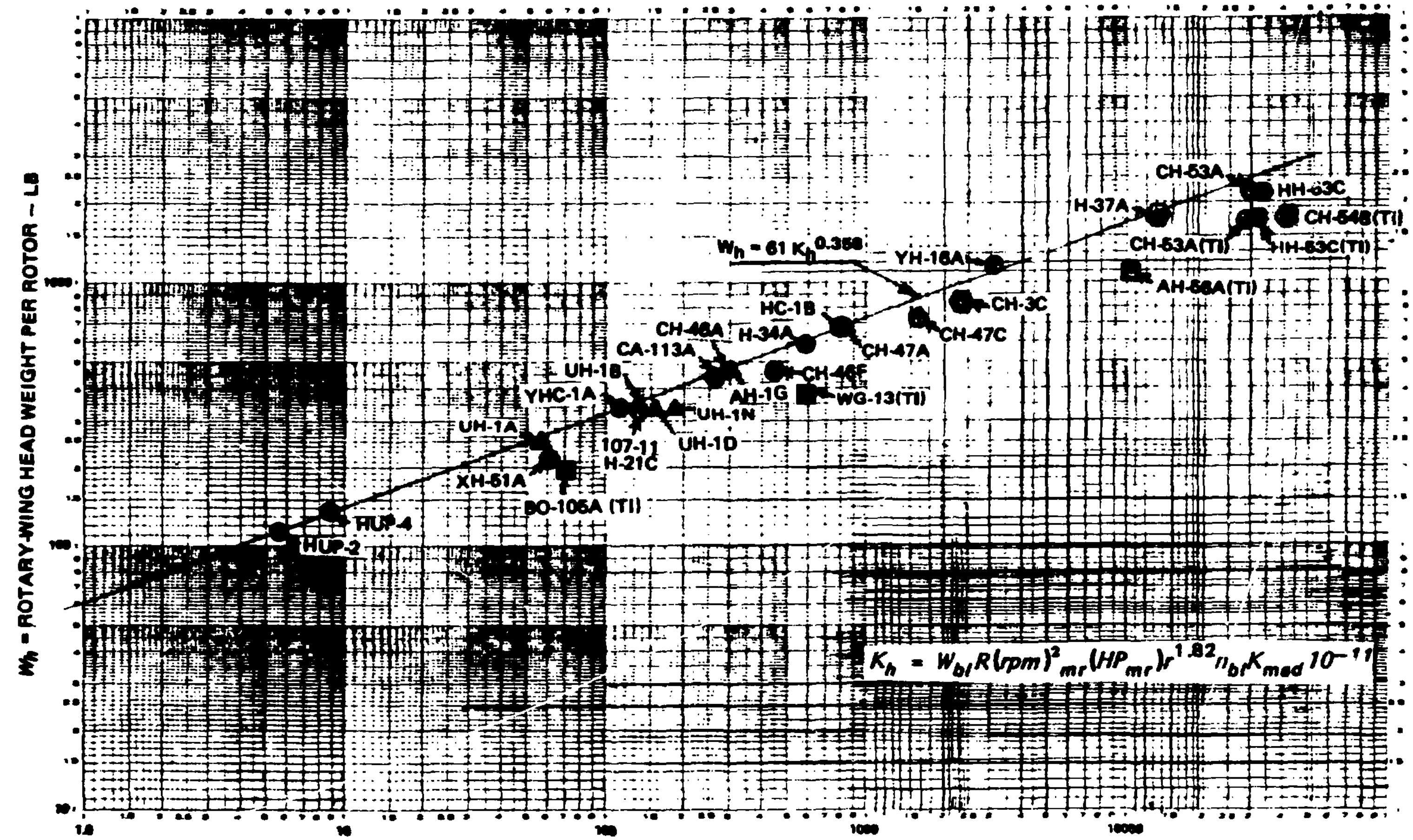


Figure 2.6 Rotary-wing hub weight trend

TABLE 2.2-BV

MAIN-ROTOR HUB AND HINGE WEIGHT ESTIMATES FOR THREE HELICOPTER PAIRS

ITEM	HELICOPTER					
	UP TO 12,000 LB		12,000 TO 30,000 LB		30,000 TO 100,000 LB	
	Mi-2	BO-105	Mi-8	UH-60A	Mi-6	CH-53E
ACTUAL WEIGHT, LB	291.1	200.5	1333.0	605.9	7331.6	3472.1
BOEING VERTOL WEIGHT FORMULA	$W_h = 61a\,[W_{bl}R(rpm)^2_{mr}HP_{mr}r^{1.82}n_{bl}^{2.5}k_{mad}10^{-11}]^{0.358}$					
PARAMETER	VALUES					
a	1.0	1.0	1.0	1.0	1.0	1.0
W_{bl}; lb	121.33	67.05	255.6/295.4	210.3	1553.8/1190.2	412.1
R; ft	23.88	16.14	34.94	26.83	57.42	39.50
rpm	246	424	192	258	120	179
HP; hp	720	690†/800††	2700	2685	12,350	12,480
r; ft	1.09	1.22	2.19	2.50	[3.27]	4.73
n_{bl}	3	4	5	4	5	7
k_{mad}	1.0	0.302	1.0	0.35	1.0	0.56
COMPUTED WEIGHT, lb	187.5	175†/184.5	938.25/988.1	601.6	3108.2/3419.5	3471.0
PREDICTED TO ACTUAL WEIGHT RATIO	0.64	0.86/0.91	0.70/0.74	0.99	0.42/0.47	1.00

NOTES:
† transmission limit
†† based on takeoff power

blades (n_{bl}) is also represented, while the influence of the rotor design is reflected through the magnitude of the first natural blade flapping frequency (ν_1).

As in the case of Eq (2.3), the values of the fixed coefficient and exponent of the various parameters were selected in order to provide the best possible correlation between predicted and actual weights of sample hubs.

The results of calculations performed for the three pairs of the compared helicopters are shown in Table 2.2-RTL. It can be seen from this table that Eq (2.7) predicts the weights of the hubs and hinges of the compared helicopters rather well – both Soviet and Western. The largest deviation occurred for the CH-53 helicopter (an under-prediction of about 19 percent). But this deviation could well result from the fact that this particular helicopter has automatically folding blades and thus, it may be expected that its hub and hinge assembly would be relatively heavier than those of its land-based counterparts.

<u>Discussion.</u> The ratios of the predicted to the actual weights of the main-rotor hub and hinges as estimated by the three considered methods for the three pairs of the compared helicopters are plotted in Fig. 2.7, where the average values and scatter bands are also indicated. A look at this figure will confirm the previous conclusion that Tishchenko's approach based on Eq (2.4) and a constant value of the k^*_h coefficient is not suitable as a tool for weight predictions of main-rotor hubs and hinges, especially for designs deviating from the conventional articulated configurations using steel as a basic material.

The Boeing-Vertol method (Eq. (2.6)) predicts the hub and hinge weights of all the compared Western helicopters very well, but underestimates these weights for Soviet designs. The RTL approach (Eq (2.7)) succeeds in uniformly well predicting the hub and hinge weights of both Western and Soviet helicopters.

2.4 Tail-Rotor Group Weight Estimates

<u>Tishchenko Formula.</u> In the Tishchenko approach, the blade weights ($n_{bl_{tr}} W_{bl_{tr}}$) and hub plus hinge weights ($W_{h_{tr}}$) are calculated separately. For the blade weights, a formula similar to Eq (2.1) is used, with the exception that it does not contain a term for high blade aspect ratio corrections, as very slender blades are not likely in the case of tail rotors. Consequently, the blade part of the tail-rotor group weight formula becomes

$$n_{bl_{tr}} W_{bl_{tr}} = k^*_{bl_{tr}} [\sigma_{tr} R_{tr}^{2.7} / (\bar{\lambda}_{tr})^{0.7}] \qquad (2.8)$$

Here, as in the case of Eq (2.1), only the geometric parameters of the tail rotor and the blade weight coefficient $k^*_{bl_{tr}}$, whose values show an even larger scatter (Fig. 2.8) than in the case of the main-rotor blades (Fig. 2.1), appear in the weight estimate equation. In spite of this, the constant value of $k^*_{bl_{tr}} = 13.8\ \mathrm{kg/m^{2.7}}$ assumed in the weight estimates of hypothetical helicopter tail-rotor blades in Table 2.10[1] is also used in the present comparison (Table 2.3-T).

TABLE 2.2-RTL

MAIN-ROTOR HUB AND HINGE WEIGHT ESTIMATES
FOR THREE HELICOPTER PAIRS

ITEM	HELICOPTER					
	UP TO 12,000 LB		12,000 TO 30,000 LB		30,000 TO 100,000 LB	
	Mi-2	BO-105	Mi-8	UH-60A	Mi-6	CH-53E
ACTUAL WEIGHT, LB	291.1	200.5	1333.0	605.9	7331.6	3472.1
RTL WEIGHT FORMULA	$W_h = 0.002116\, n_{bl}^{0.2965} R^{1.5717} V_t^{0.5217} \nu_1^{1.9550} (n_{bl} W_{bl})^{0.5292}$					
PARAMETER	VALUES					
n_{bl}	3	4	5	4	5	7
R; ft	23.88	16.14	34.94	26.83	57.42	39.50
V_t; fps	615.2	716.5	702.5	725.0	721.4	740.4
ν_1; per rev	1.03	1.12	1.03	1.02	1.03	1.04
Actual $(n_{bl} W_{bl})$; lb	364	268	1477†	841	7769†	2697
COMPUTED WEIGHT, lb	294.5	186.2	1401.2	641.1	8244.5	2799.5
PREDICTED TO ACTUAL WEIGHT RATIO	1.01	0.93	1.05	1.06	1.12	0.81

NOTE: †heavier blades.

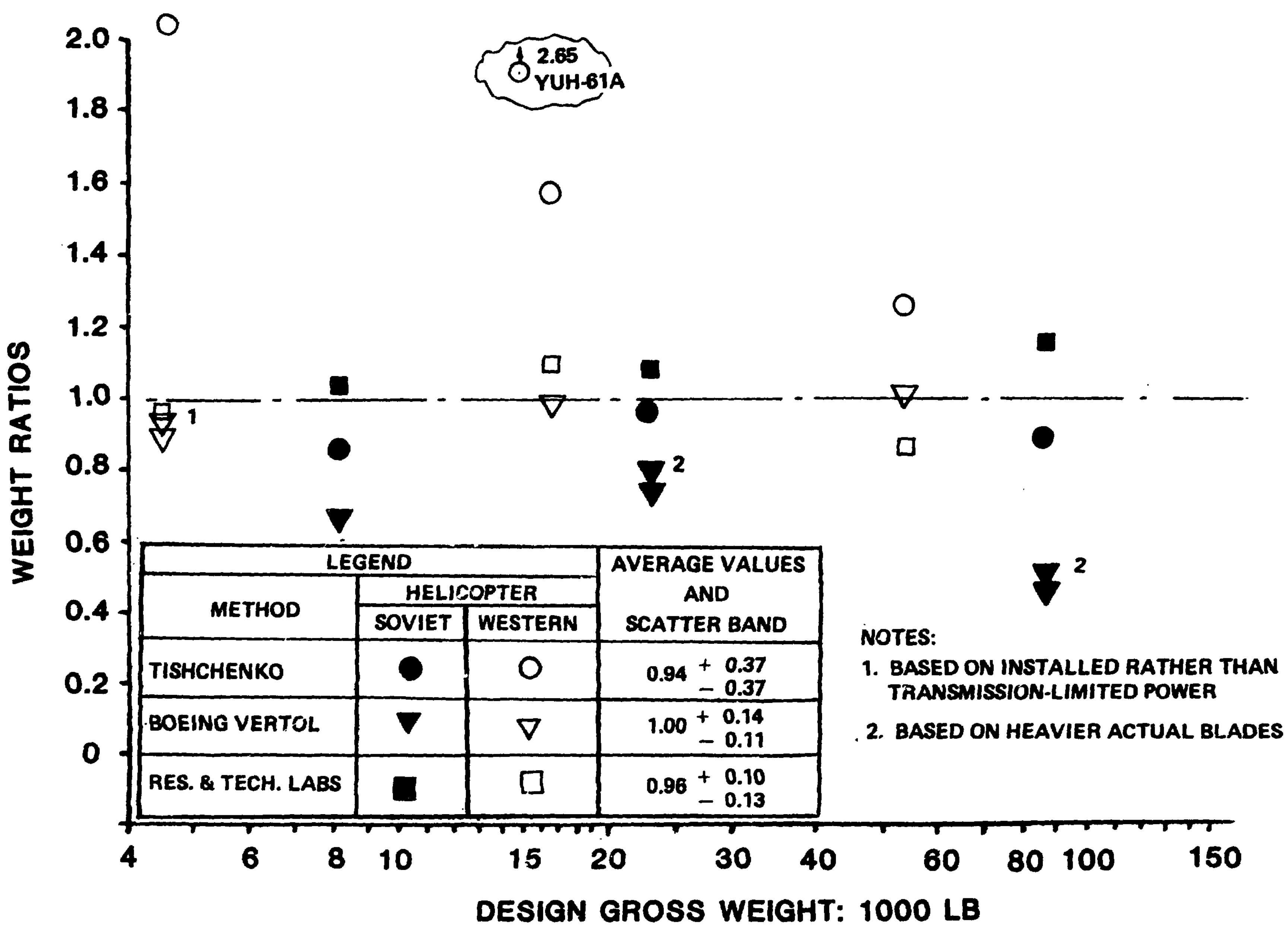


Figure 2.7 Predicted-to-actual weight ratios of main-rotor hubs and hinges

TABLE 2.3-T

TAIL-ROTOR GROUP WEIGHT ESTIMATES
FOR THREE HELICOPTER PAIRS

ITEM	HELICOPTER					
	UP TO 12,000 LB		12,000 TO 30,000 LB		30,000 TO 100,000 LB	
	Mi-2	BO-105	Mi-8	UH-60A	Mi-6	CH-53E
ACTUAL WEIGHT, LB	54.9	21.9	150.0/259.3	122.9	1123.7/1274.5	584.4
TISHCHENKO WEIGHT FORMULA	$n_{bl_{tr}} W_{bl_{tr}} = k^*_{bl_{tr}} [\sigma_{tr} R_{tr}^{2.7} / (\bar{\lambda}_{tr})^{0.7}]$ $W_{h_{tr}} = k^*_{h_{tr}} n_{bl_{tr}} [1 + 0.05(n_{bl_{tr}} - 4)] (CF_{bl_{tr}})^{1.35}$					
PARAMETER	VALUES					
$k^*_{bl_{tr}}$; kg/m$^{2.7}$	13.8	13.8	13.8	13.8	13.8	13.8
σ_{tr}	0.104	0.121	0.156/0.132	0.188	0.171	0.196
R_{tr}; m	1.35	0.95	1.80/1.95	1.67	3.35	3.04
$\bar{\lambda}_{tr}$	0.34	0.29	0.45/0.40	0.38	0.41	0.36
$n_{bl_{tr}} W_{bl_{tr}}$; kg	6.87	3.46	18.4/21.11	20.4	115.2	111.3
$k^*_{h_{tr}}$	1.15	1.15	1.15	1.15	1.15	1.15
$n_{bl_{tr}}$	2	2	4/3	4	4	4
$CF_{bl_{tr}}$; m.ton	5.6[1]	4.43	6.05[1]/15.4[1]	7.05	21.8[1]/25.3[1]	23.09
$W_{h_{tr}}$; kg	23.54	17.15	52.25/138.3	64.24	294.9/360.5	318.7
COMPUTED WEIGHT, kg	30.41	20.61	70.65/159.4	84.64	410.1/475.7	430.0
COMPUTED WEIGHT, lb	67.05	45.45	155.8/351.5	186.6	904.3/1048.9	948.1
PREDICTED TO ACTUAL WEIGHT RATIO	1.26	2.08	1.04/1.36	1.52	0.80/0.84	1.62

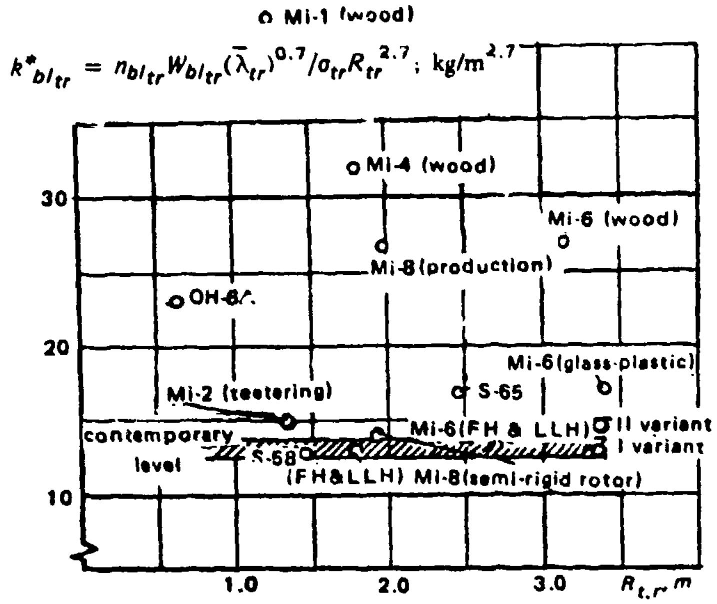


Figure 2.8 Weight coefficient of tail-rotor blades
(FH – flapping hinge; LLH – lead-lag hinge)

The weight contribution represented by tail-rotor hubs is estimated, using a formula identical to that for the main-rotor hubs and hinges (Eq (2.4)). It is rewritten here with the $k_{n_{bl}}$ coefficient explicitly expressed:

$$W_{h_{tr}} = k^*_{h_{tr}} n_{bl_{tr}} [1 + 0.05(n_{bl_{tr}} - 4)] N_{bl_{tr}}^{1.35} \tag{2.9}$$

As in Eq (2.4), the tail-rotor blade centrifugal force $N_{bl_{tr}}$ in the above equation is expressed in metric tons and the values in the square brackets are assumed as equal to one for $n_{bl_{tr}} \leqslant 4$. Since there are only two parameters ($N_{bl_{tr}}$ and $n_{bl_{tr}}$), and weight correlation is obtained through the $k^*_{bl_{tr}}$ coefficient, it may be expected that a variety of configurations, designs, and materials would result in a large scatter of $k^*_{bl_{tr}}$ values when related to existing designs. Indeed, Fig. 2.9 clearly proves that point. This obviously means that accurate predictions of the tail-rotor hub weights for new designs can only be made by selecting a $k^*_{h_{tr}}$ value from those representing similar existing designs. However, in this study (as in the case of the main-rotor hubs), a single value of $k^*_{h_{tr}} = 1.15$, as indicated in Table 2.10[1] is assumed.

Calculations of the tail-rotor blade and hub weights are shown in Table 2.3-T, and then their combined weights are compared with actual weights.

$$k^*_{h_{tr}} = \frac{W_{h_{tr}}}{n_{bl_{tr}}[1 + 0.05(n_{bl_{tr}} - 4)]\,(CF_{bl_{tr}})^{1.35}}\ ;\ \mathrm{kg/ton}^{1.35}$$

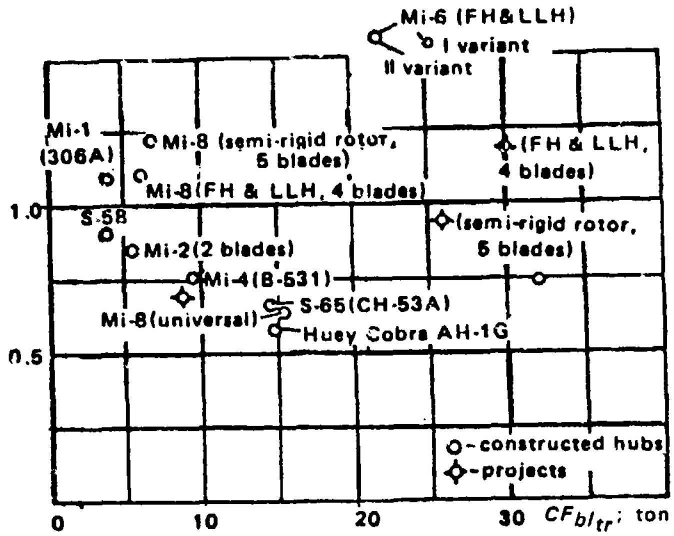


Figure 2.9 Weight coefficients of tail-rotor hubs
(FH – flapping hinge; LLH – lead-lag hinge)

It can be seen from this table that again, the Tishchenko formula with $k^*_{bl_{tr}} = 13.8$ and $k^*_{h_{tr}} = 1.15$ greatly overpredicts the actual weights of the tail-rotor group for Western helicopters (e.g., for the BO-105, by more than 100 percent). Performance with respect to Soviet helicopters is somewhat better, but still far from satisfactory: for the Mi-2, the overprediction is about 26 percent; for the Mi-6, underprediction by about 16 to 20 percent; and only for the Mi-8 was the prediction good (4 percent difference) for the lighter of the two systems. It appears, hence, that as in the case of main-rotor hubs, the Tishchenko approach does not provide a reasonable tool for predicting tail-rotor group weights of new designs. Since the predicted values depend so much on the values of the weight coefficient, perhaps better results could have been obtained for new designs if an existing tail-rotor group as similar as possible to the envisioned new concept can be located, and weight coefficients calculated from that baseline case, and then applied to the new concept.

<u>Boeing Vertol Formula.</u> The Boeing Vertol formula represents a different philosophy from that visible in the Soviet approach. This is apparent from the following:

$$W_{tr} = 14.2a\,[r_{tr}^{0.25}(0.01HP_{tr})^{0.5}\,0.01\,V_{t_{tr}}\,0.1\,R_{tr}\,n_{bl_{tr}}\,c_{tr}]^{0.67} \qquad (2.10)$$

In this formula the blade weights, and hub and hinge weights are contained in a single expression. There is no reference to the blade centrifugal force; instead, there are several parameters reflecting the planform geometry of the tail rotor as a whole. In this respect, r_{tr} indicates the radius of the blade attachment, $n_{bl_{tr}}$ the number of blades, R_{tr} the blade radius, and c_{tr} the blade chord. In addition to these geometric parameters, Eq (2.10) contains $V_{t_{tr}}$ indicating the tail-rotor tip speed, and HP_{tr} the horsepower absorbed by the tail rotor. As in the previously discussed Boeing-Vertol formula, satisfactory correlation of the estimated weights with those of existing helicopters is obtained through selected values of the fixed coefficient and exponents of particular parameters, and the product of those parameters.

As seen in Fig. 2.10, there is a larger scatter of statistical values (+28, −20 percent) than in the case of main-rotor blades and hubs.

The results of the application of Eq (2.10) to the three pairs of compared helicopters are shown in Table 2.3-BV.

It can be seen from this table that (similar to the case of the main-rotor hubs) Eq (2.10) greatly under-predicts the tail-rotor weights of Soviet helicopters – at times, by more than 50 percent. Only for the lighter tail-rotor set of the Mi-8 does the predicted weight come close to the actual value, but is still lower by approximately 16 percent. This may indicate that statistically, the weights of Soviet tail-rotor assemblies are much higher than those of their Western counterparts. With respect to the latter, one can see from Table 2.3-BV that for the three helicopters, the predicted values are within the margin of scatter indicated in Fig. 2.10 (−6 percent for the BO-105, +12 percent for the UH-60A, and 26 percent for the CH-53E).

<u>RTL Formula.</u> The RTL formula for predicting the tail-rotor group weight is as follows:

$$W_{tr} = 1.3778\, R_{tr}^{0.0897} (HP_{mr}\, R_{mr}/V_{t_{mr}})^{0.8951} \qquad (2.11)$$

Eq (2.11) clearly indicates that the RTL approach represents a philosophy different from that of either Tishchenko or Boeing Vertol. In this equation, one finds a term representing three main-rotor parameters (power, radius, and tip speed), while the tail rotor is represented through a single parameter of its radius. As in the previously discussed RTL formulae, coefficient and exponent values were selected in order to provide the best possible fit of predicted and actual values of existing tail-rotor groups.

It can be seen from Table 2.3-RTL that Eq (2.11) consistently under-predicts tail-rotor group weights. However, the degree of under-prediction varies within wide limits. For instance, for the CH-53E and the lighter tail-rotor group of the Mi-8, the predicted to the actual weight ratios are good (0.91) and very good (0.95), respectively; while for the heavier tail-rotor group of the Mi-8, this ratio drops to 0.55. For the Mi-6, the predicted weight amounts to 65 percent of the lighter tail-rotor group for the design helicopter power of 11,000 hp. Should 13,000 hp, corresponding to the higher engine rating, be assumed, than the weight ratio would improve to 76 percent.

TABLE 2.3-BV

TAIL ROTOR GROUP WEIGHT ESTIMATES
FOR THREE HELICOPTER PAIRS

ITEM	HELICOPTER					
	UP TO 12,000 LB		12,000 TO 30,000 LB		30,000 TO 100,000 LB	
	Mi-2	BO-105	Mi-8	UH-60A	Mi-6	CH-53E
ACTUAL WEIGHT, LB	54.9	21.9	150.0/259.3	122.9	1123.7/1274.5	584.4
BOEING VERTOL WEIGHT FORMULA	$W_{tr} = 14.2a\,[r_{tr}^{0.25}(0.01\,HP_{tr})^{0.5}0.01\,V_{t_{tr}}\,0.1R_{tr}\,n_{bl_{tr}}\,c_{tr}]^{0.67}$					
PARAMETER	VALUES					
a	1.0	1.0	1.0	1.0	1.0	1.0
r; ft	[0.55]	[0.50]	[1.00]	[0.73]	[1.46]	[1.62]
HP_{tr}; hp	[80]	[90]	[400]	[350]	[1400]	[1500]
$V_{t_{tr}}$; fps	672.5	717.5	758.4	685.4	777.6	732.0
R_{tr}; ft	4.43	3.115	6.41	5.5	10.99	10.0
$n_{bl_{tr}}$	2	2	3	4	4	4
c_{tr}; ft	0.72	0.59	0.89	0.81	1.48	1.28
COMPUTED WEIGHT, lb	31.6	23.37	125.8	108.7	507.0	432.3
PREDICTED TO ACTUAL WEIGHT RATIO	0.59	1.06	0.84/0.49	0.88	0.45/0.40	0.74

NOTE: $HP_{tr} \equiv$ transmission limit per rotor.

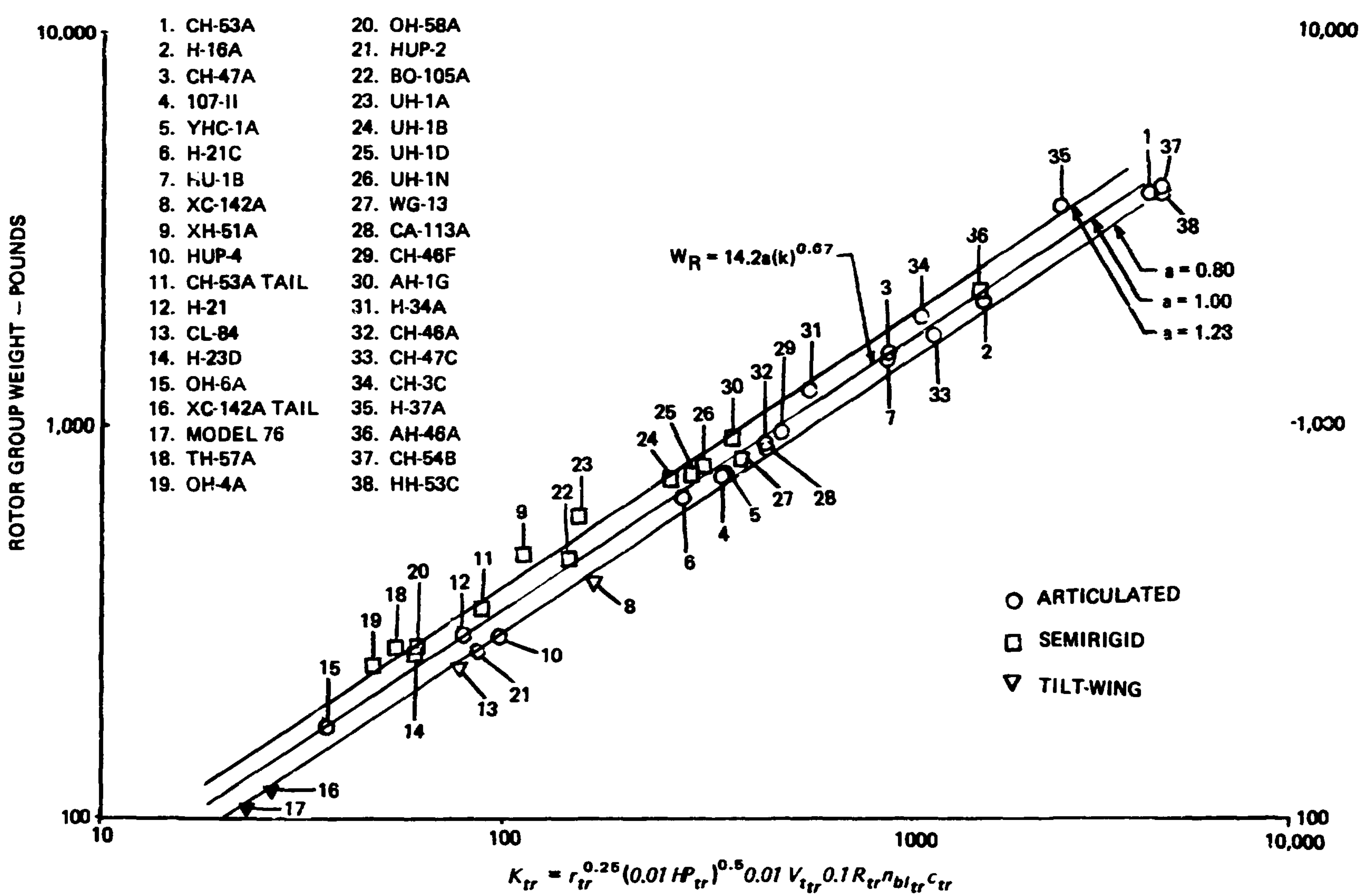


Figure 2.10 Rotor group weight trend

TABLE 2.3-RTL

TAIL-ROTOR GROUP WEIGHT ESTIMATES
FOR THREE HELICOPTER PAIRS

ITEM	HELICOPTER					
	UP TO 12,000 LB		12,000 TO 30,000 LB		30,000 TO 100,000 LB	
	Mi-2	BO-105	Mi-8	UH-60A	Mi-6	CH-53E
ACTUAL WEIGHT, LB	54.9	21.9	150.0/259.3	122.9	1123.7/1274.5	584.4
RTL WEIGHT FORMULA	$W_{tr} = 1.3778 R_{tr}^{0.0897} (HP_{mr} R_{mr}/V_{t_{mr}})^{0.8951}$					
PARAMETER	VALUES					
R_{tr}; ft	4.43	3.115	5.9/6.41	5.5	10.00/10.33	10.0
HP ; hp	800	600	3000	2828	11,000	11,570
R_{mr}; ft	23.88	16.14	34.94	26.83	57.42	39.50
$V_{t_{mr}}$; fps	615.0	716.5	702.5	725	721.4	740
COMPUTED WEIGHT, lb	39.7	15.8	142.6/143.7	103.1	734.8†/730.8	533.1
PREDICTED TO ACTUAL WEIGHT RATIO	0.74	0.72	0.95/0.55	0.84	0.65†/0.57	0.91

NOTE: †for HP = 13,000 hp, the referenced values would be 852.4 lb and 0.76, respectively.

__Discussion.__ The results of the calculations performed in Tables 2.3-T, 2.3-BV, and 2.3-RTL are summarized in Fig. 2.11, where the average values and scatter bands are also shown. It is apparent from this figure that none of the three methods accurately predicts the actual weights of the tail-rotor group. But, of the three, Tishchenko's approach (with constant values of the $k^*_{bl_{tr}}$ and $k^*_{h_{tr}}$ coefficients) appears to give results so unpredictable that its value as a tool for preliminary design weight estimates becomes doubtful.

The Boeing-Vertol and RTL methods both give better results in the tail-rotor group weight estimates of Western helicopters, as well as the lighter assembly weights of the Soviet medium weight (Mi-8) and heavy weight (Mi-6) helicopters; thus indicating that the weights predicted by either of these methods represent levels possible to achieve through careful design. As for a direct comparison of the Boeing-Vertol and RTL formulae; it appears that in the cases considered here, the weight prediction methods established by RTL appear to have a slight advantage.

2.5 Fuselage Weight Estimates

__Tishchenko.__ A general expression for predicting the weight of the fuselage as given in Ref. 1 is as follows:

$$W_f = k^*_f \, W_{gr}^{0.25} \, S_f^{0.86} \, L^{0.16(1 + \alpha)} \tag{2.12}$$

In this approach, the significant parameters characterizing the considered helicopter are: (1) its design gross weight (W_{gr}), in kg; (2) wetted area of the fuselage (S_f) in m^2; and (3) distance between the rotor axes (L) in m. For single-rotor configurations, L measures the distance between the main and tail-rotor axes; while for tandems, L represents the distance between the axes of the front and rear rotors. Furthermore, α, appearing in the exponent of L, is $\alpha = 0$ for single-rotor helicopters, $\alpha = 0.2$ for tandems, and $\alpha = 0.05$ for side-by-side configurations.

It can be seen that Eq (2.12) takes into account some important design parameters, but it neglects the influence of such factors as the type of fuselage structure and material. However, since most of the fuselages of existing helicopters are of the semi-monocoque type made of aluminum alloys, scatter of the computed k^*_f values is not as great as in the previously considered weight coefficients using the Tishchenko approach (see Fig. 2.12). In Table 2.10[1], $k^*_f = 1.36$ is assumed for weight estimates of hypothetical helicopters. Consequently, the same k^*_f value was also used in this comparative study.

Computations of fuselage weights and their comparisons with actual weights are shown in Table 2.4-T. It can be seen from this table that in the present case, the consistency of the predictions, although still far from perfect, is much better than the Tishchenko weight-prediction methods examined so far. If the same weight coefficient value used for other helicopters ($k^*_f = 1.36$) is used for the Mi-6, the largest under-estimate would amount to about 23 percent. For the other compared helicopters, the under-estimate would range from about 2 to 18 percent. This may simply imply that the Mi-6 fuselage

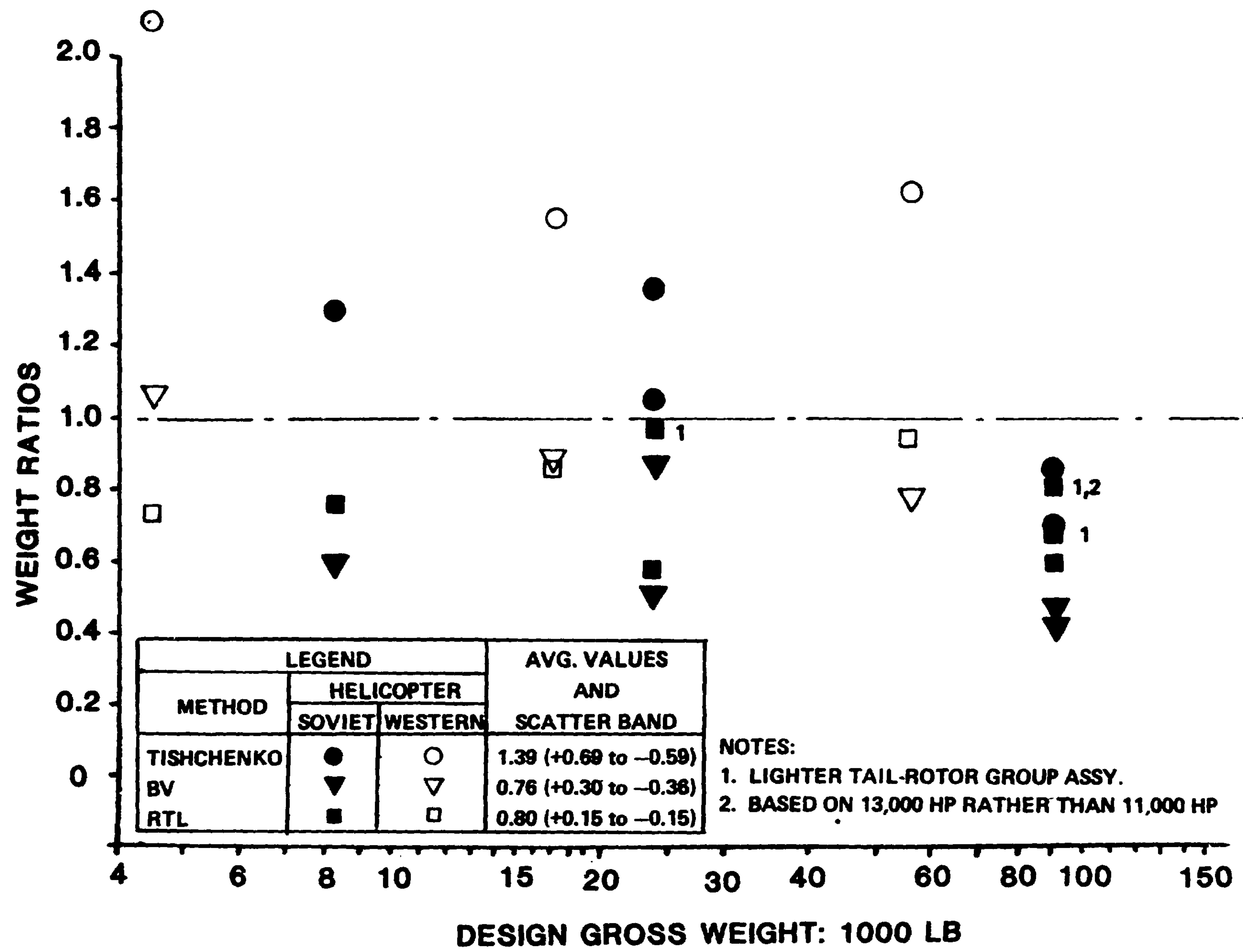


Figure 2.11 Predicted-to-actual weight ratios of the tail-rotor group

$$k_f^* = \frac{W_f}{W_{gr}^{0.25} S_f^{0.88} L^{0.16}}, \frac{k_g}{k_g^{0.25} m^{1.92}}$$

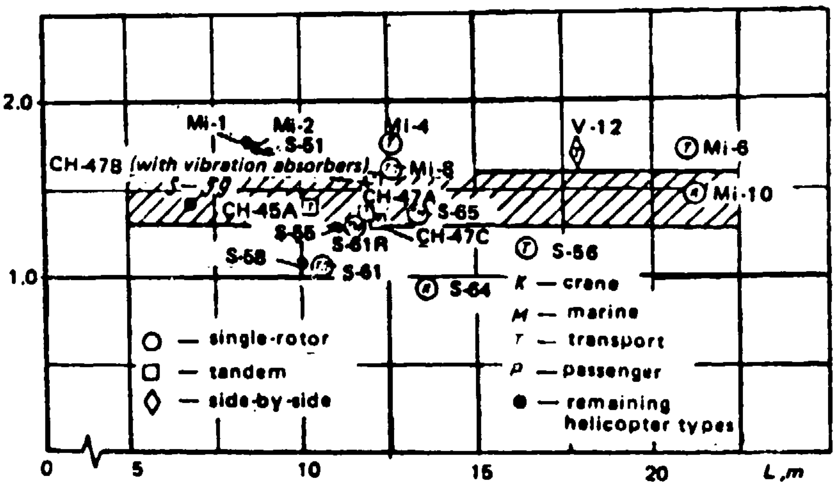


Figure 2.12 Fuselage weight coefficients k^*_f used in Eq (2.12) which take into account the influence of parameters characterizing fuselage wetted area S_f and distance L between rotor axes on fuselage weight (hatched area corresponds to the contemporary level of transport helicopters)

is designed with less emphasis on structural weight reductions than other helicopters. The next largest fuselage weight under-prediction in Table 2.4-T is for the CH-53E (approximately 23 percent if W_{gr} = 56,000 lb, and 18 percent if W_{gr} = 73,500 lb is used in Eq (2.12)). However, in the latter case, the fuselage may be expected to be somewhat heavier because of the tail-folding that is necessary for carrier operations.

<u>Boeing Vertol.</u> The Boeing-Vertol approach toward fuselage weight prediction goes into much more detail than Eq (2.12), as the weights of the fuselage sub-groups are estimated separately.

The weight of the body group is given by the following expression from Ref. 2:

$$W_{bg} = 125\{[(10^{-4} W_{gr}) n_{ult} (10^{-3} S_f)(L_c + L_{rw} + \Delta CG)]^{0.5} \log V_{max}\}^{0.8} \qquad (2.13)$$

where W_{gr} is the design gross weight; n_{ult} is the ultimate load factor; S_f is the fuselage area in sq.ft, including fairing and pods; L_c is the distance in ft from the fuselage nose to the end of the cabin floor; L_{rw} is the length in ft of the ramp well; ΔCG is the center of gravity range in ft; and V_{max} is the maximum level flying speed in knots.

TABLE 2.4-T

FUSELAGE WEIGHT ESTIMATES
FOR THREE HELICOPTER PAIRS

ITEM	HELICOPTER					
	UP TO 12,000 LB		12,000 TO 30,000 LB		30,000 TO 100,000 LB	
	Mi-2	BO-105	Mi-8	UH-60A	Mi-6	CH-53E
ACTUAL WEIGHT, LB	981.2	657.3	3230.3	2284.0	13,384.4	8704.0
TISHCHENKO WEIGHT FORMULA	$W_f = k^*_f W_{gr}^{0.25} S_f^{0.88} L^{0.16(1+\alpha)}$					
PARAMETER	VALUES					
k^*_f; $kg/kg^{0.25} m^{1.92}$	1.36	1.36	1.36	1.36	1.36	1.36
W_{gr}; kg	3700	2014.4† 2319.3††	11,100	7460.3	41,000	25,396.8† 33,332.2††
S_f; m^2	40.0	30.7	105.0	95.0	295.0	[220.0]
L; m	8.77	7.10	12.64	9.91	21.08	14.97
α	0.0	0.0	0.0	0.0	0.0	0.0
COMPUTED WEIGHT, kg	385.7	253.8†/262.9††	1258.3	1003.4	4699.1	3047.7/3263.0†
COMPUTED WEIGHT, lb	850.5	559.6/579.7	2774.6	2212.5	10361.4	6720.2/7195†
PREDICTED TO ACTUAL WEIGHT RATIO	0.87	0.85†/0.88†	0.86	0.98	0.77	0.77/0.82†

NOTES: †normal gross weight; ††maximum flying gross weight.

The statistical correlation of Eq (2.13) with weight data from existing helicopters is shown in Fig. 2.13, where one may note that with a constant coefficient of 125, $0.9 \leq a \leq 1.1$ encloses the scatter area. For weight estimates in preliminary design, $a = 1.0$ is recommended and thus, this value was assumed in Table 2.4-BV.

The weight of the horizontal empennage (tail) is estimated separately through the following formula[2]:

$$W_{ht} = S_{ht}(sw)_{ht} \tag{2.14}$$

where S_{ht} is the horizontal tail projected area in sq.ft, and $(sw)_{ht}$ is the specific weight in lb/ft^2 (a value of 1.1 lb/ft^2 is recommended for fixed surfaces, 1.3 lb/ft^2 for movable ones, and 1.6 lb/ft^2 for those having a separate stabilizer[2]). In Table 2.4-BV, $(sw)_{ht} = 1.1$, and $(sw)_{ht} = 1.3$ was assumed.

The weight of the engine structure is still subdivided for estimating purposes ir) smaller entities. In Ref. 2, this is done by separately computing the weights of the engine mounts (W_{em}), engine nacelles (W_n), and the air induction system (W_{ai}).

The weight of the engine mount is given as follows:

$$W_{em} = n_{eng}(W_{eng}\,n_{clf})^{0.41} \tag{2.15}$$

where n_{eng} is the number of engines, W_{eng} is the weight of one engine in lb, and n_{clf} is the crash load factor. According to Boeing Vertol, n_{clf} vlaues should be 8 foı civil, and 20 for military helicopters[4].

Although a more elaborate expression is given in Ref. 4 for estimating the weight of the nacelles, the one given here from Ref. 2 is simpler:

$$W_n = n_{eng}\,S_n\,k_n \tag{2.16}$$

where S_n is the external area in sq.ft, and k_n is the specific weight of the nacelle structure in lb/ft^2. This value for helicopters may be assumed as 1.0 lb/ft^2.

The weight of the air induction system can be expressed as:

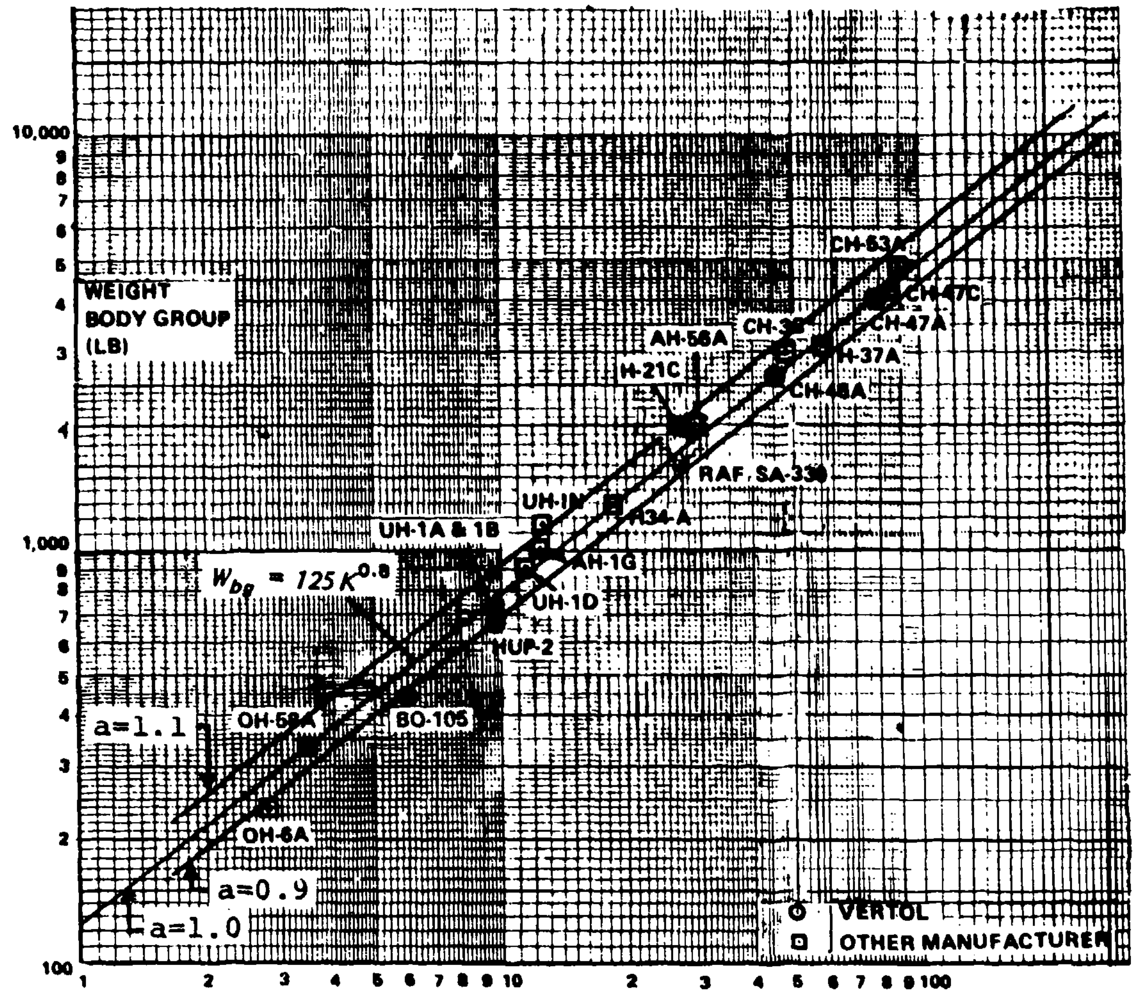
$$W_{ai} = n_{eng}\,D_{eng}\,L_{ad}\,k_{ai} \tag{2.17}$$

where the new symbol L_{ad} is the length of an air auct in ft, D_{eng} is the engine diameter in ft, and k_{ai} is the specific weight in lb/ft^2. This value for helicopters may be assumed as 0.85 lb/ft^2.

The total weight of the fuselage will obviously be obtained by adding Eqs (2.13) through (2.17):

$$W_f = W_{bg} + W_{ht} + W_{em} + W_n + W_{ai} \tag{2.18}$$

The steps required to compute the fuselage weights of the three pairs of compared helicopters according to Eq (2.18) are given in Table 2.4-BV.



$$K = \left[\frac{W_{gr}}{10^4} n_{ult} \frac{S_f}{10^3}\left(L_c + L_{rw} + \Delta CG\right)\right]^{0.5} \log V_{max}$$

Figure 2.13 Body group weight trend

TABLE 2.4-BV

FUSELAGE WEIGHT ESTIMATES FOR THREE HELICOPTER PAIRS

ITEM		HELICOPTER					
		UP TO 12,000 LB		12,000 TO 30,000 LB		30,000 TO 100,000 LB	
		Mi-2	BO-105	Mi-8	UH-60A	Mi-6	CH-53E
ACTUAL WEIGHT, LB		981.2	657.3	3230.3	2284.0	13,384.4	8704.0
BOEING VERTOL WEIGHT FORMULA		$W_f = W_{bg} + W_{ht} + W_{em} + W_n + W_{ei} = 125a\ [(10^{-4}W_{gr})n_{ult}(10^{-3}S_f)(L_c + L_{rw} + \Delta CG)]^{0.5} \log V_{max}\ ^{0.8} + S_{ht}(sw)_{ht} + n_{eng}(W_{eng}n_{clf})^{0.41} + n_{eng}S_nk_n + n_{eng}D_{eng}L_{ed}k_{ei}$					
PARAMETER		VALUES					
a		1.05	1.05	1.05	1.00	1.05	1.10
W_{gr};	lb	8158	4442	24,255	16,835	90,405	56,000
n_{ult};	g's	[4.125]	5.25	[4.125]	5.25	[4.125]	4.5
S_f;	sq.ft	430.4	330.3	1129.8	1022.2	3174.2	[2367.2]
L_c;	ft	15.2	11.43	30.60	24.4	55.1	38.0
L_{rw};	ft	2.4	2.57	5.25	4.0	19.4	13.7
ΔCG;	ft	[0.5]	[0.8]	[1.0]	[1.0]	[1.5]	[1.5]
V_{max};	kn	113	145	135	167	162	170
W_{bg};	lb	861.9	643.6	2683.6	2203.8	9444.2	65[illegible]6
S_{ht},	ft	8.73	12.33*	15.5	55.0	54.3	65.8
$(sw)_{ht}$;	lb/ft²	1.1	1.1	1.1	1.3	1.3	1.3
W_{ht};	lb	9.6	13.57	17.05	71.5	70.6	85.5
n_{eng}		2	2	2	2	2	3
W_{eng};	lb	304	158	727	415	2921	720
n_{clf};	g's	[12]	[8]	[12]	20	[12]	20
W_{em};	lb	57.7	37.4	82.6	73.9	146.0	152.1
S_n;	sq.ft	[2.6]	13.8**	[49.0]	28.9	[121.9]	52
k_n;	lb/ft²	1.0	1.0	1.0	1.0	1.0	1.0
W_n;	lb	5.2	13.8	98.0	57.8	121.9	156.0
D_{eng};	ft	1.89	1.75	2.1	2.1	3.7	1.7
L_{ed};	ft	[2.0]	[1.6]	[2.2]	[2.3]	[4.7]	[3.0]
k_{ei};	lb/ft²	0.85	0.85	0.85	0.85	0.85	0.85
W_{ei};	lb	6.4	4.8	7.9	8.2	29.6	13.0
COMPUTED WEIGHT, LB		940.8	670.4	2889.2	2415.2	9812.3	6977.2
PREDICTED/ACTUAL WEIGHT		0.96	1.02	0.90	1.06	0.73	0.80

NOTES: *includes end-plates **$n_n = 1.0$ (common nacelle for both engines)

It can be seen from this table that the fuselage weights of the two Western helicopters (BO-105 and UH-60A) as well as that of the Mi-2 are predicted with acceptable accuracy (–4, +6 percent). The fuselage weight of the Mi-8 is under-predicted by about 10 percent, but the highest under-predictions occur for the Mi-6 (about 27 percent) and for the CH-53E. The explanation for this is similar to that given in the discussion of the Tishchenko approach; namely, that it simply appears that the design of the Mi-6 is generally heavy; and carrier operation requirements result in higher weights for the CH-53E fuselage.

RTL. Similar to the Boeing Vertol method, separate expressions are given for various sub-groups in the RTL approach to fuselage weight estimates. For instance, the weight of the body group is expressed as follows:

$$W_{bg} = 10.13(10^{-3}\,W_{gr_{max}})^{0.5719}\,n_{ult}^{0.2238}\,L^{0.5558}\,S_f^{0.1534}\,I_{ramp}^{0.5242} \tag{2.19}$$

At first glance, the above formula appears to closely resemble Eq (2.13) of Boeing Vertol. However, there are some differences in both expressions. For instance, in Eq (2.19), the gross weight is represented by the maximum flying weight ($W_{gr_{max}}$) – not by the design weight as in Eq (2.13); L is the total length of the fuselage, in Eq (2.19); and I_{ramp} indicates whether there is a ramp (I_{ramp} = 2.0), or no ramp (I_{ramp} = 1.0) in the fuselage. However, n_{ult} and S_f in both equations stand for ultimate load factor and fuselage wetted area, respectively. Furthermore, there is no term reflecting the flight speed.

The weight of the horizontal tail is given here as:

$$W_{ht} = 0.7176S_{ht}^{1.1881}\,AR_{ht}^{0.3172} \tag{2.20}$$

When comparing this equation with Eq (2.14), one would note that a combination of projected area and aspect ratio is used in Eq (2.20) instead of the projected area and specific weight expressed in Eq (2.14).

The weight of the vertical tail is computed separately in the RTL approach, and expressed as

$$W_{vt} = 1.0460S_{vt}^{0.9441}\,AR_{vt}^{0.5332}\,n_{gtr}^{0.7058} \tag{2.21}$$

where S_{vt} is the projected area of the vertical tail in sq.ft; AR_{vt} is the aspect ratio; and n_{gtr} is the number of tail-rotor gearboxes.

The weight of the engine cowling is expressed solely as a function of the nacelle wetted area (S_{nw}):

$$W_c = 0.2315S_{nw}^{1.3476} \tag{2.22}$$

This differs from the Boeing-Vertol approach in that a combination of the nacelle wetted area and structural specific weight is used in Eq (2.16).

The weight of the nacelle less cowling ($W_{n\text{-}c}$) is given as a function of the engine weight (W_{eng}) and number of engines:

$$W_{n\text{-}c} = 0.0412\, W_{eng}^{\ 1.1433}\, n_{eng}^{\ 1.3762} \tag{2.23}$$

The above equation is also at variance with the corresponding one: i.e, Eq (2.15) of the Boeing Vertol approach.

The total weight of the fuselage group is obviously the sum of the weights of all its sub-groups:

$$W_f = W_{bg} + W_{ht} + W_{vt} + W_c + W_{n\text{-}c} \tag{2.24}$$

The parameters appearing in Eqs (2.19) through (2.23), the weights of particular sub-groups, and the total fuselage weights of the compared helicopters are shown in Table 2.4-RTL.

It can be seen from this table that the RTL method generally predicted the fuselage weight of all the compared helicopters very well (within +5 to −3 percent), with the exception of the Mi-8, where the weight is over-predicted by about 25 percent. This deviation can be explained in part by the assumption of the ultimate load factor (n_{ult} = 4.125). Should this value amount to 3.0, then the corresponding estimated fuselage weight would come down to W_f = 3793.5 lb; with a corresponding weight ratio of 1.17.

<u>Discussion.</u> The predicted to actual fuselage weight ratios computed by the three considered methods are shown in Fig. 2.14, where average values and scatter bands are also indicated. One can see from this figure that the RTL approach seems to lead to the closest prediction of the actual fuselage weights for both Western and Soviet helicopters, with the exception of the Mi-8. The Boeing-Vertol method deals relatively well with the two pairs of small and medium helicopters, but under-predicts the fuselage weight of the large ones by about 20 percent. The Tishchenko formulae (with a fixed weight coefficient) consistently under-predicted the fuselage weights. For the pair of small helicopters, the under-estimation amounts to about 12 percent, while for the Mi-6—CH-53E pair, it rises to over 20 percent. Selection of a value higher than 1.36 for the k^*_f coefficient indicated in Table 2.10 of Ref. 1 would improve the overall accuracy of their fuselage weight predictions, except for the UH-60A, where k^*_f = 1.36 leads to an almost perfect match.

2.6 Landing Gear Weight Estimates

<u>General.</u> The basic philosophies of Tishchenko and Boeing Vertol with respect to landing gear weight estimation are quite similar. In both approaches, the group weight is directly related to the helicopter gross weight through a coefficient of proportionality where the value depends on the type of landing gear (skid, fixed-wheel, or retractable). The RTL approach takes into consideration not only gross weight, but also additional design parameters. Similarities and differences exhibited by all three approaches will be brought into focus in the following discussion.

TABLE 2.4-RTL

FUSELAGE WEIGHT ESTIMATES
FOR THREE HELICOPTER PAIRS

ITEM		HELICOPTER					
		UP TO 12,000 LB		12,000 TO 30,000 LB		30,000 TO 100,000 LB	
		Mi-2	BO-105	Mi-8	UH-60A	Mi-6	CH-53E
ACTUAL WEIGHT, LB		981.2	657.3	3230.3	2284.0	13,384.4	8704.0
RTL WEIGHT FORMULA		$W_f = 10.13(10^{-3} W_{grmax})^{0.5718} n_{ult}^{0.2238} L^{0.5558} S_f^{0.1534} I_{ramp}^{0.5242} + 0.7176 S_{ht}^{1.1881} AR_{ht}^{0.3173} + 1.0460 S_{vt}^{0.9441} AR_{vt}^{0.5332} n_{gtr}^{0.7058} + 0.2315 S_{nw}^{1.3476} + 0.0412 W_{eng}^{1.1433} n_{eng}^{1.3762}$					
PARAMETER		VALUES					
W_{grmax}	lb	8175	5114	26,460	20,250	93,700	73,500
η_z		[4.125]	4.83	[4.125]	4.36	[3.0]	2.85
L	ft	39.2	28.1	60.1	46.2	108.9	73.3
S_f	ft^2	430.4	217.0/330.3	1030.0	829.3	3174.2	2281.9
I_{Rmp}		1.0	1.0	2.0	1.0	2.0	2.0
W_{bg}	lb	906.8	535.6/569.6	3676.6	1856.4	11,668.7	7658.3
S_{ht}	ft^2	8.7	8.6	15.5	45.0	54.3	56.0
AR_{ht}		4.7	5.0	4.9	4.0	3.4	3.13
W_{ht}	lb	15.3	15.4	30.8	102.6	121.8	125.1
S_{vt}	ft^2	5.9	5.0	11.3	32.3	68.7	72.3
AR_{vt}		7.0	2.31	2.5	2.07	2.6	2.16
η_{gtr}		2.0	2.0	2.0	2.0	2.0	2.0
W_{vt}	lb	25.72	12.2	27.14	66.3	154.0	146.4
S_{nw}	ft^2	2 X 2.6	13.8	2 X 49.0	104.5	2 X 121.9	178.0
W_c	lb	7.2	8.6	111.7	121.8	343.5	249.6
W_{eng}	lb	304	158	727	415	2921	720
n_{eng}		2	2	2	2	2	3
$W_{n\text{-}c}$	lb	73.8	34.9	199.9	105.3	755.2	345.4
COMPUTED WEIGHT, LB		1028.8	606.7/640.7	4046.4	2252.4	13,043.2	8522.8
PREDICTED/ACTUAL WEIGHT		1.05	0.92/0.97	1.25	0.99	0.97	0.98

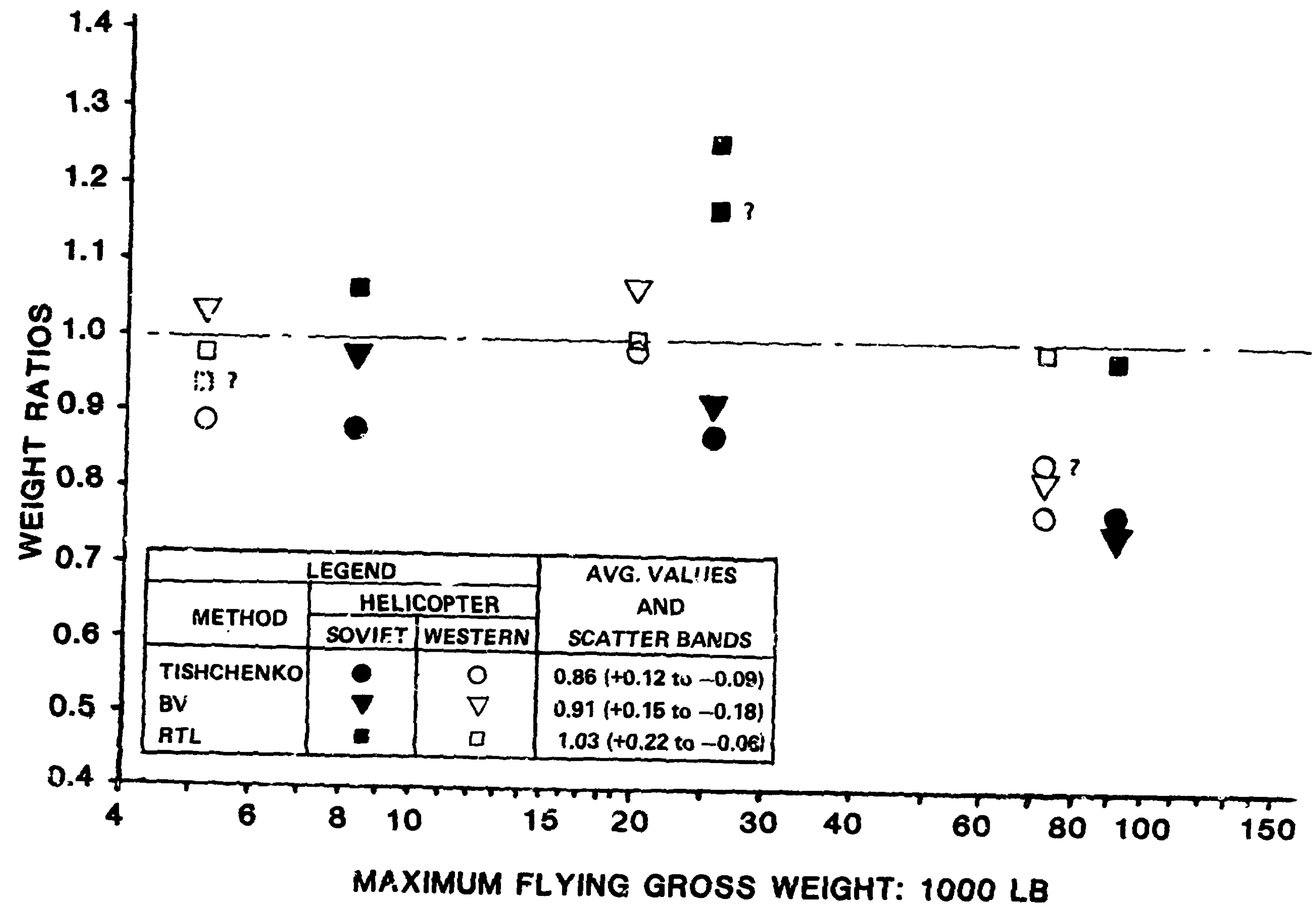


Figure 2.14 Predicted-to-actual weight ratios of fuselages

Tishchenko. The landing gear weight is assumed by Tishchenko to represent a fixed fraction of the aircraft design gross weight:

$$W_{lg} = k_{lg} W_{gr} \tag{2.25}$$

where the value of the weight coefficient k_{lg} varies, depending on the helicopter configuration (single-rotor, tandem, or side-by-side), and the type of landing gear (wheel or skid). For a single-rotor, wheel-type landing gear, $k_{lg} = 0.02$ was recommended on p. 86 of Ref. 1, and was used in the weight estimates of the hypothetical helicopters (Table 2.10[1]). For the skid-type landing gear, $k_{lg} = 0.01$ as suggested in Ref. 1, is used in this comparison. In examining Fig. 2.15 one would find that the suggested value of $k_{lg} = 0.02$ may be somewhat optimistic, especially for the retractable type.

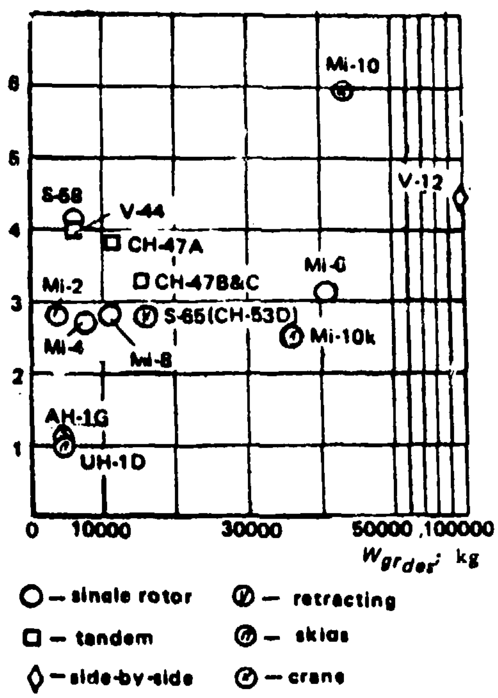


Figure 2.15 Weight coefficients of helicopter landing gears

Inputs required for landing-gear weight estimates are shown in Table 2.5-T. Using the k_{lg} values suggested above, it is noted that the landing-gear weights of all the considered helicopters is grossly underpredicted. An exception is unexpectedly provided by the CH-53E where, in spite of a retractable-type landing gear, the landing-gear weight is closer to the estimated value than in the remaining five cases.

TABLE 2.5-T

LANDING GEAR WEIGHT ESTIMATES
FOR THREE HELICOPTER PAIRS

ITEM	HELICOPTER					
	UP TO 12,000 LB		12,000 TO 30,000 LB		30,000 TO 100,000 LB	
	Mi-2	BO-105†	Mi-8	UH-60A	Mi-6	CH-53E
ACTUAL WEIGHT; lb	228.4	104.2	685.3	457.6	2802.6	1218.7
TISHCHENKO WEIGHT FORMULA	$W_{lg} = k_{lg} W_{gr}$					
PARAMETER	VALUES					
k_{lg}; kg/kg	0.02	0.01	0.02	0.02	0.02	0.02
W_{gr}; kg	3700	2014.5	11,100	7460.3	41,000	25,396.8
COMPUTED WEIGHT, kg	74.0	20.1	220.0	149.2	820.0	507.9
COMPUTED WEIGHT, lb	163.17	44.4	485.1	329.0	1808.1	1120.0
PREDICTED TO ACTUAL WEIGHT RATIO	0.74	0.43	0.71	0.72	0.65	0.92

NOTE: † skid-type, all the rest fixed wheel type; except for the CH-53E which has retractable wheel gear.

Boeing Vertol. As previously indicated, the weight of the landing gear in the Boeing-Vertol approach is also expressed as a fraction of the gross weight (assumed, in this case, to be represented by the design gross weight) as in Tishchenko's formula:

$$W_{lg} = k_{lg} W_{gr} \tag{2.26}$$

It is stated in Ref. 2 that the k_{lg} coefficient will normally vary between 0.015 and 0.050, depending on the design limit sink speed and the complexity of the system. Conventional landing gear without retraction, operating on improved runways normally run between 0.015 and 0.04. Retraction usually adds another 0.005 to 0.01. Skid-type landing gears usually weigh about 0.015 times the design gross weight. Furthermore, in Ref. 2, a table is included as a guide in selecting the k_{lg} values. The data given in that table are plotted here in Fig. 2.16.

On the basis of Fig. 2.16 and inputs from Ref. 2, the following values of the k_{lg} coefficient were used in the calculations presented in Table 2.5-BV: skid gear – k_{lg} = 0.015; fixed-wheel gear – k_{lg} = 0.03; retractable gear – k_{lg} = 0.035.

It can be seen from this table that using the a priori pre-selected values of the k_{lg} coefficient, the landing-gear weights of two Soviet and two Western helicopters are predicted with reasonable accuracy. However, the weight of a skid gear for the BO-105 is greatly under-predicted (by about 36 percent) and the weight of the retractable CH-53E landing gear was over-predicted by about 60 percent. It appears that in spite of retraction in the latter case, the landing-gear structure is exceptionally light, as its relative weight amounts to 0.022 -- much less than for the typical fixed landing gears (Fig. 2.16).

RTL. The RTL formula for predicting landing-gear weights are more elaborate than those of Tishchenko and Boeing Vertol. There are separate expressions for wheel and skid types, and they contain more parameters than just gross weight and weight coefficient. Thus, for the wheel type, the weight formula is:

$$W_{lg_w} = 36.76(W_{gr_{max}}/1000)^{0.719}\, n_{wl}^{0.4628}\, I_{rlg}^{0.0773} \tag{2.27}$$

and, for the skid type:

$$W_{lg_s} = 6.894(W_{gr_{max}}/1000)^{1.0532}\, n_{zl}^{0.3704}\, I_{sip}^{0.1484} \tag{2.27a}$$

where, in the above formula, the reference gross weight represents the maximum flying weight; n_{wl} is the number of wheeled landing gear legs; I_{rlg} is the retraction landing-gear coefficient (yes = 2, no = 1); n_{zl} is the skid landing-gear load factor; and I_{sip} is the rotor type coefficient (I_{sip} = 1.0 for stiff inplane rotors, and (I_{sip} = 2.0 for soft inplane rotors).

Parametric values assumed for landing-gear weight estimation for the three pairs of compared helicopters as well as the results of the calculations are shown in Table 2.5-RTL.

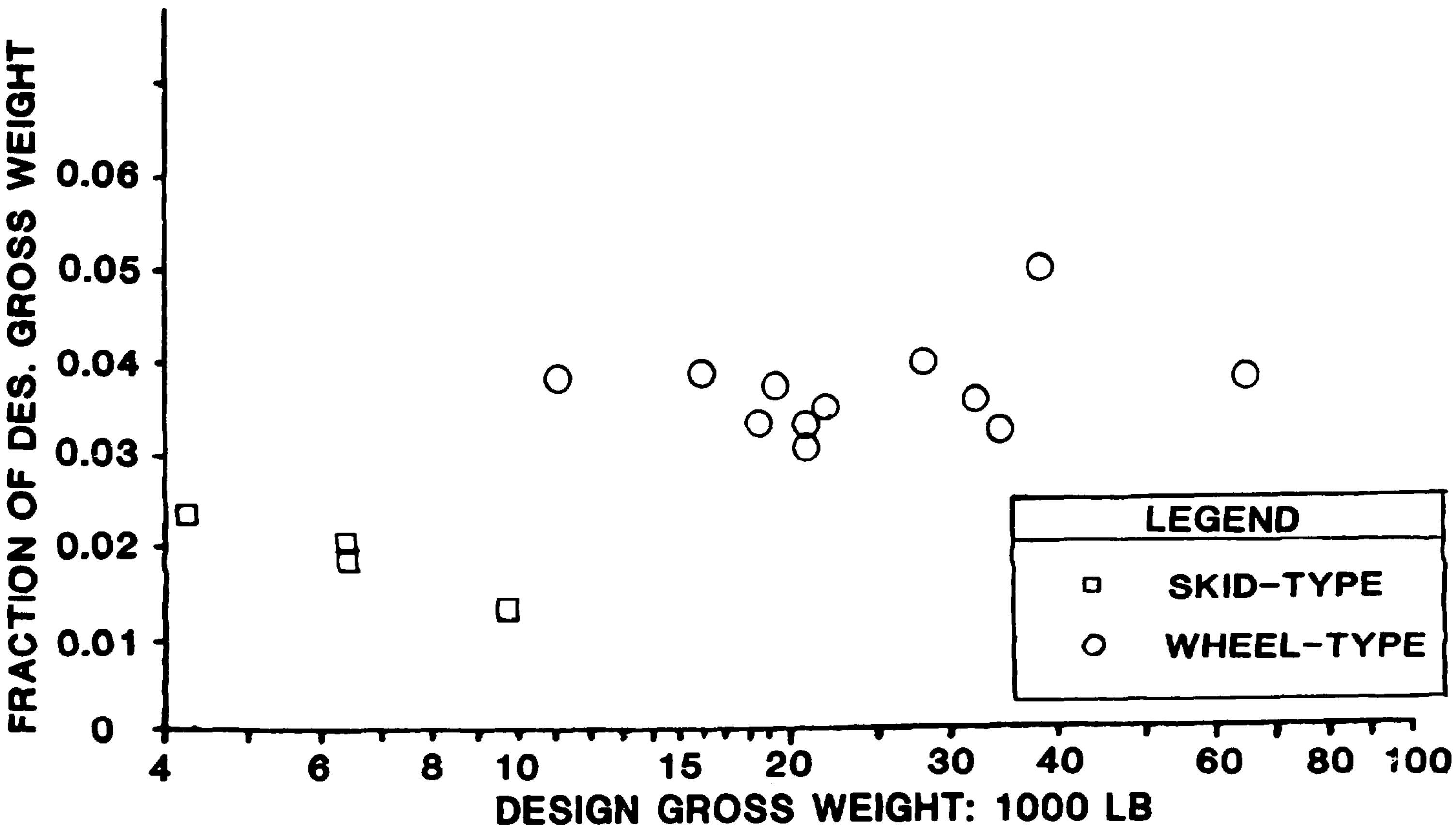


Figure 2.16 Relative landing-gear weight

TABLE 2.5-BV

LANDING GEAR WEIGHT ESTIMATES
FOR THREE HELICOPTER PAIRS

ITEM	HELICOPTER					
	UP TO 12,000 LB		12,000 TO 30,000 LB		30,000 TO 100,000 LB	
	Mi-2	BO-105	Mi-8	UH-60A	Mi-6	CH-53E
ACTUAL WEIGHT, LB	228.4	104.2	685.3	457.6	2802.6	1218.7
BOEING VERTOL WEIGHT FORMULA	$W_{lg} = k_{lg} W_{gr}$					
PARAMETER	VALUES					
k_{lg} lb/lb	0.03	0.015	0.03	0.03	0.03	0.035
W_{gr} lb	8158	4442	24,255	16,835	90,405	56,000
COMPUTED WEIGHT, lb	244.7	66.6/94.5	727.6	505.0	2712.2	1960
PREDICTED TO ACTUAL WEIGHT RATIO	1.07	0.64/0.91	1.06	1.10	0.97	1.6

TABLE 2.5-RTL

LANDING GEAR WEIGHT ESTIMATES
FOR THREE HELICOPTER PAIRS

ITEM	HELICOPTER					
	UP TO 12,000 LB		12,000 TO 30,000 LB		30,000 TO 100,000 LB	
	Mi-2	BO-105	Mi-8	UH-60A	Mi-6	CH-53E
ACTUAL WEIGHT, LB	228.4	104.2	685.3	457.6	2802.6	1218.7
RTL WEIGHT FORMULA	Wheel: $36.76(W_{grmax}/1000)^{0.719} n_{wl}^{0.4626} I_{lg}^{0.0773}$; Skid: $6.894(W_{grmax}/1000)^{1.0532} n_{zl}^{0.3704} I_{sip}^{0.1484}$					
PARAMETER	VALUES					
W_{grmax} lb	8175	5114	26,455	20,250	93,700	73,500
n_{wl}	3	–	3	3	3	3
I_{lg}	1.0	–	1.0	1.0	1.0	2.0
n_{zl}	–	4.83	–	–	–	–
I_{sip}	–	1.3	–	–	–	–
COMPUTED WEIGHT, lb	276.8	71.6	644.0	531.4	1598.7	1416.5
PREDICTED TO ACTUAL WEIGHT RATIO	1.21	0.69	0.94	1.16	0.57	1.16

A glance at this table indicates that, in general, Eqs (2.27) and (2.27a) are no better in predicting landing-gear weights than Eqs (2.25) and (2.26); although in the particular case of the CH-53E, Eq (2.27) over-predicts the landing-gear weight by a much smaller margin (16 percent) than the Boeing-Vertol formula (60 percent). At the same time, the landing gear weight of the Mi-6 was under-predicted by about 43 percent, while the Boeing approach shows an under-prediction of only 3 percent.

Discussion. An overall comparison of the three methods of landing-gear weight prediction can be best made by looking at Fig. 2.17, where average values and scatter bands are also shown. Here, it is obvious that none of the three considered approaches leads to consistently accurate weight predictions. Keeping this in mind, it can be seen that the Tishchenko formula (with the suggested k_{lg} values) consistently under-predicts landing-gear weights. An increase in the k_{lg} level would result in a better agreement with actual weights.

Both the Boeing Vertol and RTL formulae at times under-predict and over-predict landing-gear weights. It appears, however, that on the average, deviations associated with the RTL approach are slightly smaller than those of Boeing Vertol.

2.7 Drive System

Tishchenko. For single-rotor helicopters, separate formulae are given in Ref. 1 for estimating the weight of the main-rotor gearbox,

$$W_{mgb} = k^*_{mgb} n_{mgb} (\alpha_Q M_{av})^{0.8} \tag{2.28}$$

intermediate gearbox,

$$W_{igb} = k^*_{igb} n_{igb} (\alpha_Q M_{eq})^{0.8} \tag{2.29}$$

where $M_{eq} = 716.2(HP_{tr}/rpm_{sh_{tr}})$;

tail-rotor gearbox,

$$W_{trgb} = k^*_{trgb} M_{tr}^{0.8} \tag{2.30}$$

where $M_{tr} = 716.2(HP_{tr}/rpm_{tr})$, and

the transmission shaft,

$$W_{sh} = k_{sh} L_{sh} M_{ult}^{2/3} \tag{2.31}$$

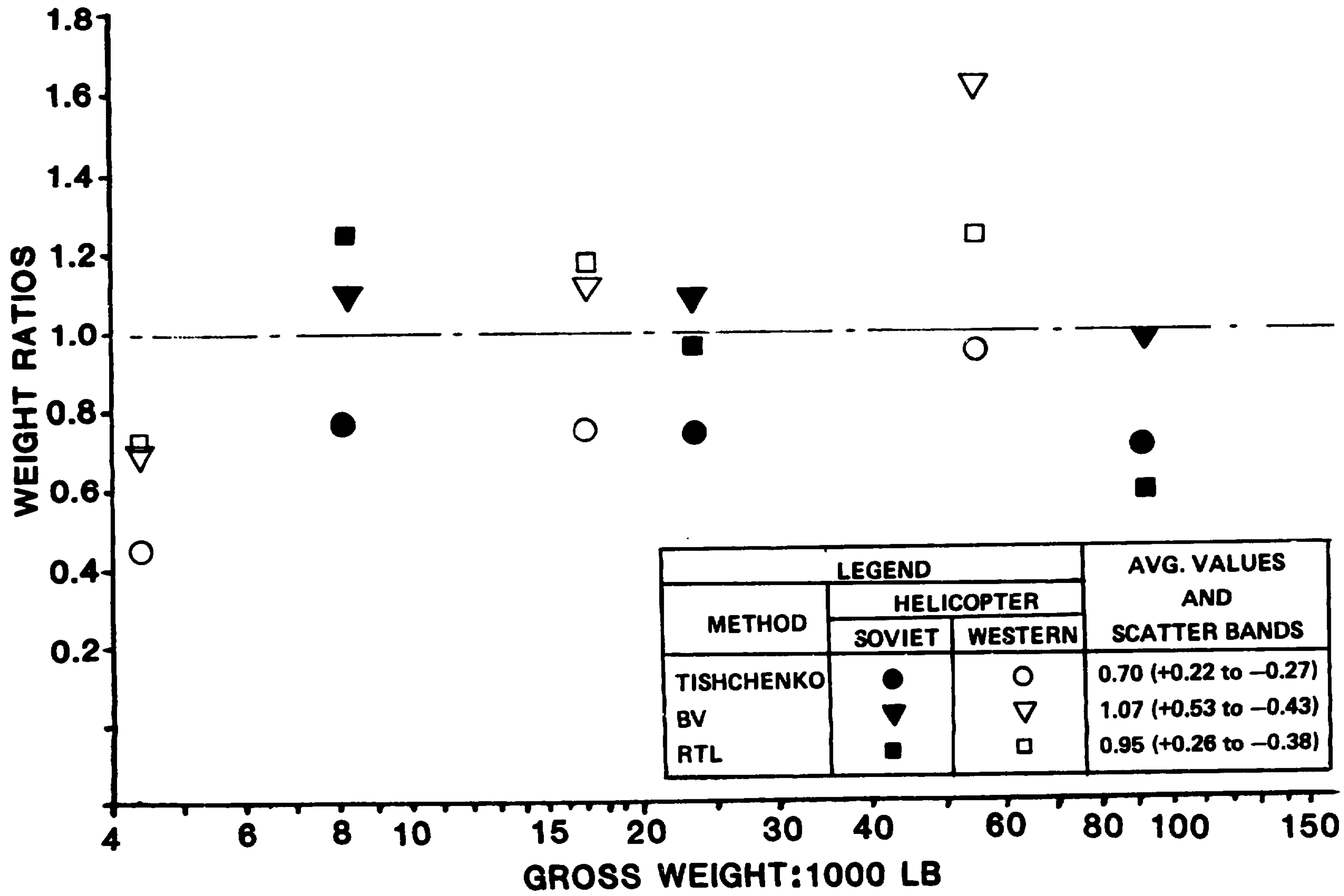


Figure 2.17 Predicted-to-actual weight ratios of landing gears

The weight of the whole drive system is obtained as the sum of Eqs (2.28) through (2.31):

$$W_{ds} = W_{mgb} + W_{igb} + W_{trgb} + W_{sh} \tag{2.32}$$

In the above equations, n with an appropriate subscript is the number of the considered gearboxes, α_Q is a coefficient reflecting excess torque, M with an appropriate subscript is torque in kg-m, HP_{tr} is the horsepower required by the tail rotor, and L is the length of the shaft in m. As usual, k's are the various weight coefficients which, for existing helicopters are shown in Figs. 2.18 through Fig. 2.21.

It can be seen from Fig. 2.18 that the k^*_{mgb} values (with the exception of the Mi-2) remain flat with respect to the torque level, and the scatter of points within each type of gearbox is relatively small. The values of $k^*_{mgb} = 0.465$ and $\alpha_Q = 1.0$ given for the single-rotor helicopters in Table 2.10[1] are also assumed here.

$$k^*_{mgb} = W_{mgb}/M_{mr}^{0.8};\ \mathrm{kg/(kg\text{-}m)^{0.8}}$$

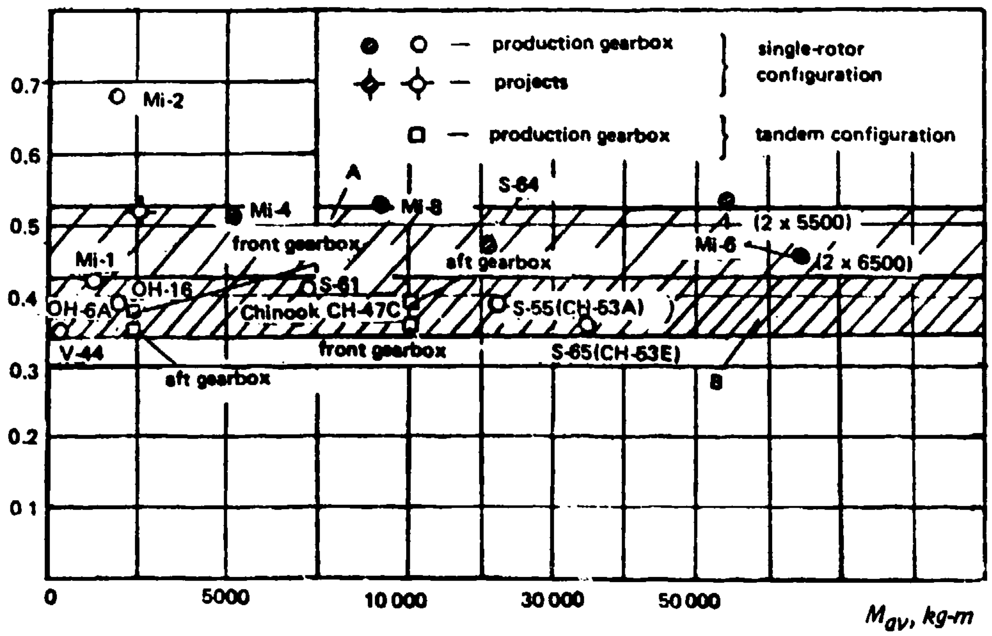


Figure 2.18 Weight coefficients k^*_{mgb} of helicopter main gearboxes (weight of the Chinook aft gearbox is with extended rotor shaft): A – Configuration with single gearbox; B – Configuration with several gearboxes in the main-rotor transmission

Fig. 2.19 clearly suggests that values of the k^*_{igb} coefficients for intermediate gearboxes sharply increase with decreasing torque. Consequently, instead of taking a constant k^*_{igb} value for all the compared helicopters regardless of their size, it would be more appropriate to assume that k^*_{igb} varies with torque in the manner shown by the broken line in Fig. 2.19. Constant values of $k^*_{igb} = 0.85$ were assumed in Table 2.10[1], and were also taken here for the two pairs of larger helicopters; while for the Mi-2 – BO-105 pair, W_{igb} was computed twice: once for $k^*_{igb} = 0.85$, and then $k^*_{igb} = 1.2$ for the Mi-2, and 1.25 for the BO-105 as indicated by the trend curve in Fig. 2.19. Although these new coefficients would increase the predicted intermediate gearbox weights by about 45 percent, this increase would have only a minimal effect (about one percent) on the overall weight of the drive system. Consequently, only $k^*_{igb} = 0.85$ is shown in Table 2.6-T.

$$k^*_{igb} = W_{igb}/n_{igb}(M_{eq})^{0.8}, \ \mathrm{kg/(kg\text{-}m)^{0.8}}$$

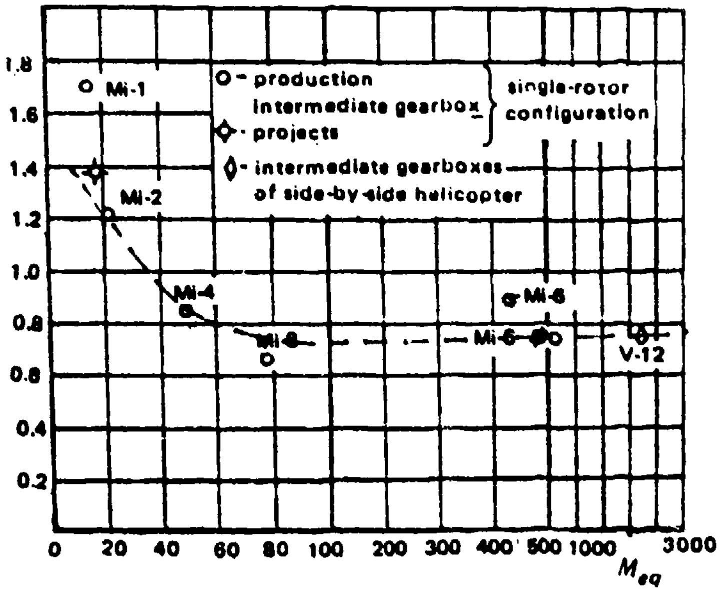


Figure 2.19 Weight coefficients of intermediate gearboxes

As can be seen from Fig. 2.20, the tail-rotor gearbox weight coefficients also show a general tendency to increase with diminishing torque levels. However, within a wide range of torque values – from that of the Mi-2 to that of the Mi-6 – a constant value for k^*_{trgb} can be assumed. Thus, following the example shown in Table 2.10 of Ref. 1, $k^*_{trgb} = 0.65$ is taken in the calculations shown in Table 2.6-T.

TABLE 2.6-T

DRIVE SYSTEM WEIGHT ESTIMATES
FOR THREE HELICOPTER PAIRS

ITEM	HELICOPTER					
	UP TO 12,000 LB		12,000 TO 30,000 LB		30,000 TO 100,000 LB	
	Mi-2	BO-105	Mi-8	UH-60A	Mi-6	CH-53E
ACTUAL WEIGHT, LB	750.2	435.9	1987.3	1465.5	8410.2/8472.0	6257.1
TISHCHENKO WEIGHT FORMULA	$W_{ds} = W_{mgb} + W_{igb} + W_{trgb} + W_{sh} = k^*_{mgb} n_{mgb} (\alpha_Q M_{eq})^{0.8} + k^*_{igb} n_{igb} (\alpha_Q M_Q)^{0.8} + k^*_{trgb} M_{tr}^{0.8} + k_{sh} M_{ult}^{2/3}$					
PARAMETER	VALUES					
k^*_{mgb}	0.465	0.465	0.465	0.465	0.465	0.465
n_{mgb}	1.0	1.0	1.0	1.0	1.0	1.0
α_Q	1.0	1.0	1.0	1.0	1.0	1.0
M_{eq}; kg-m	1890[1]	1002.3	9290[1]	6749	54,800[1]	45,214
W_{mgb}; kg	194.4†	117.0	694.8	538.1	2873.0	2464.2
k^*_{igb}	0.85	0.85	0.85	0.85	0.85	0.85
n_{igb}	1.0	1.0	1.0	1.0	1.0	1.0
α_Q	1.0	1.0	1.0	1.0	1.0	1.0
M_{eq}; kg-m	21.5[1]	15.3	79[1]	48.3	430[1]	[275.4]
W_{igb}; kg	9.9	7.5	28.0	18.9	108.7	76.1
k^*_{trgb}	0.65	0.65	0.65	0.65	0.65	0.65
M_{tr}; kg-m	36[1]	[17]	177[1]	134.8	1274[1]	1035.6
W_{tgb}; kg	11.4	6.3	40.0	32.9	198.2	167.8
k_{sh}	0.07	0.07	0.07	0.07	0.07	0.07
L_{sh}	8.1	[5.9]	12.4	[10.7]	20.4	[15.8]
M_{ult} kg-m	67.1††	41.0	330[1]	[166.6]	1490[1]	[950]
W_{sh}; kg	9.4	4.9	41.5	22.7	186.3	106.9
COMPUTED WEIGHT; kg	326.4	134.4	804.3	612.6	3367.1	2815.0
COMPUTED WEIGHT; lb	719.7	296.4	1773.5	1350.8	7424.5	6207.1
PREDICTED TO ACTUAL WEIGHT RATIO	0.96	0.68	0.89	0.92	0.88/0.88	0.99

NOTES: †Actual W_{mgb} = 284 kg, resulting from box configuration and use of Mi-1 gears
††Estimated as 36 X $(330/177)_{Mi\text{-}8}$

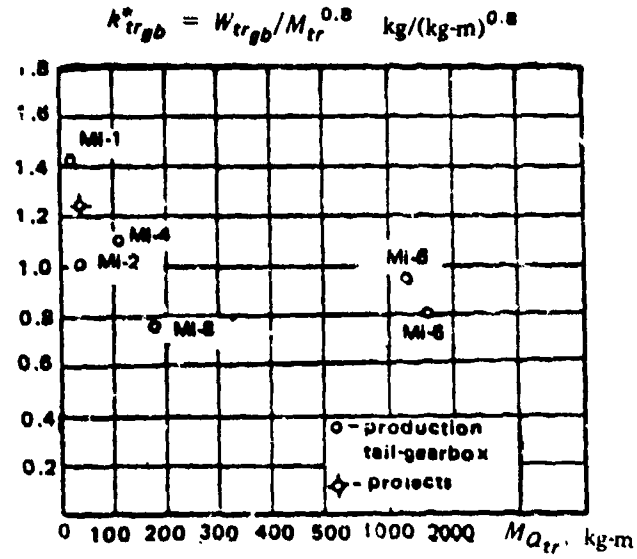


Figure 2.20 Tail-rotor gearbox weight coefficients of single-rotor helicopters

The values of the shaft weight coefficient shown in Fig. 2.21 are relatively constant with the ultimate (destructive) torque levels. Consequently, again following the example given in Table 2.10[1], k_{sh} = 0.07 kg/m(kg-m)$^{2/3}$ was assumed in the calculations shown in Table 2.6-T.

The parametric values, weights of the drive system subcomponents, and total weights of the systems as a whole are also shown in this table. Here, it can be seen that with the exception of the BO-105, the drive system weights of all the other compared helicopters were predicted quite well – mostly below a few percent of the actual weights.

Boeing Vertol. In the Boeing approach, the overall drive-system weight of single-rotor configurations is predicted by separately estimating the weights of the main-rotor and tail-rotor drive systems. The following formula from Ref. 2 is given for the preliminary and auxiliary drive system weight in lbs, including gearboxes, accessory drives, shafting oil, supports, etc:

$$(W_{ds})_{mr} = 250a_{mr}[(HP_{mr}/rpm_{mr})z_{mr}^{0.25}k_t]^{0.67} \tag{2.33}$$

where a_{mr} is the adjustment factor (assumed here as a_{mr} = 1.0), HP_{mr} is the drive system horsepower ratings (for tandems, it amounts to 1.2 times the takeoff rating), rpm_{mr} is the main-rotor rpm at takeoff, z_{mr} is the number of stages in the main-rotor drive*, and k_t is the configuration factor: k_t = 1.0 for single, and 1.3 for tandem helicopters.

*For helicopters of 10,000-lb gross weight, z_{mr} = 2 is assumed; for 10,000 to 30,000-lb gross weight, z_{mr} = 3 to 4, and for helicopters having gross weights over 30,000 lb, z_{mr} = 4 to 5.

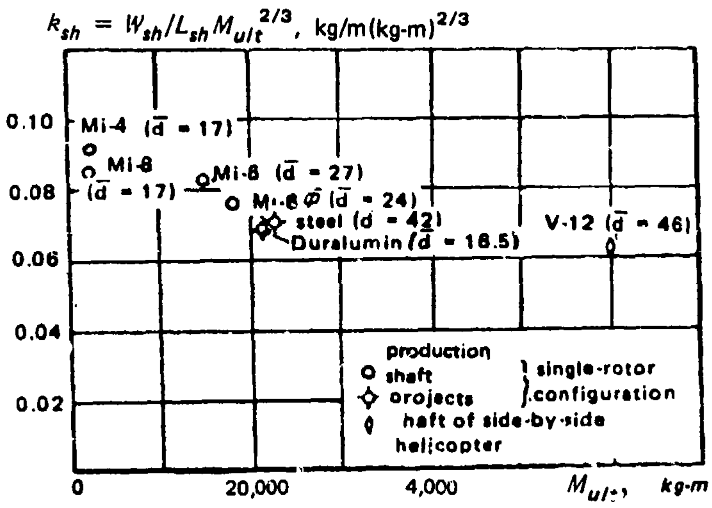


Figure 2.21 Shaft weight coefficients for several Soviet helicopters

Statistical correlation of data supporting Eq (2.33) is shown in Fig. 2.22.

The weight of the tail-rotor drive system (including shafting) is expressed in lbs as

$$(W_{ds})_{tr} = a_{tr}\,[1.1(HP_{tr}/rpm_{tr})]^{0.8} \qquad (2.34)$$

where the adjustment factor is assumed as $a_{tr} = 0.9$; HP_{tr} is the tail-rotor horsepower which, for preliminary design estimates can be assumed as equal to 10 percent of the installed power; and rpm_{tr} is the tail-rotor design rpm.

Statistical correlation in support of Eq (2.34) is shown in Fig. 2.23 from which one can see the rationale for selecting $a_{tr} = 0.9$ as a representative value of that coefficient.

The overall weight of the helicopter drive system is obtained as a sum of Eqs (2.33) and (2.34):

$$W_{ds} = (W_{ds})_{mr} + (W_{ds})_{tr} \qquad (2.35)$$

The parametric values used in weight predictions as well as the weight of the subassemblies and the whole drive system are shown in Table 2.6-BV.

The general drive-system weight of the compared helicopters shown in this table was reasonably well predicted by the Boeing-Vertol approach. One exception is the Mi-2, where weight under-prediction amounted to about 19 percent. However, this exception can be explained by the fact that the main-rotor gearbox is heavier than it should be because some gears were used from the Mi-1 helicopter and were not specially designed for the Mi-2.

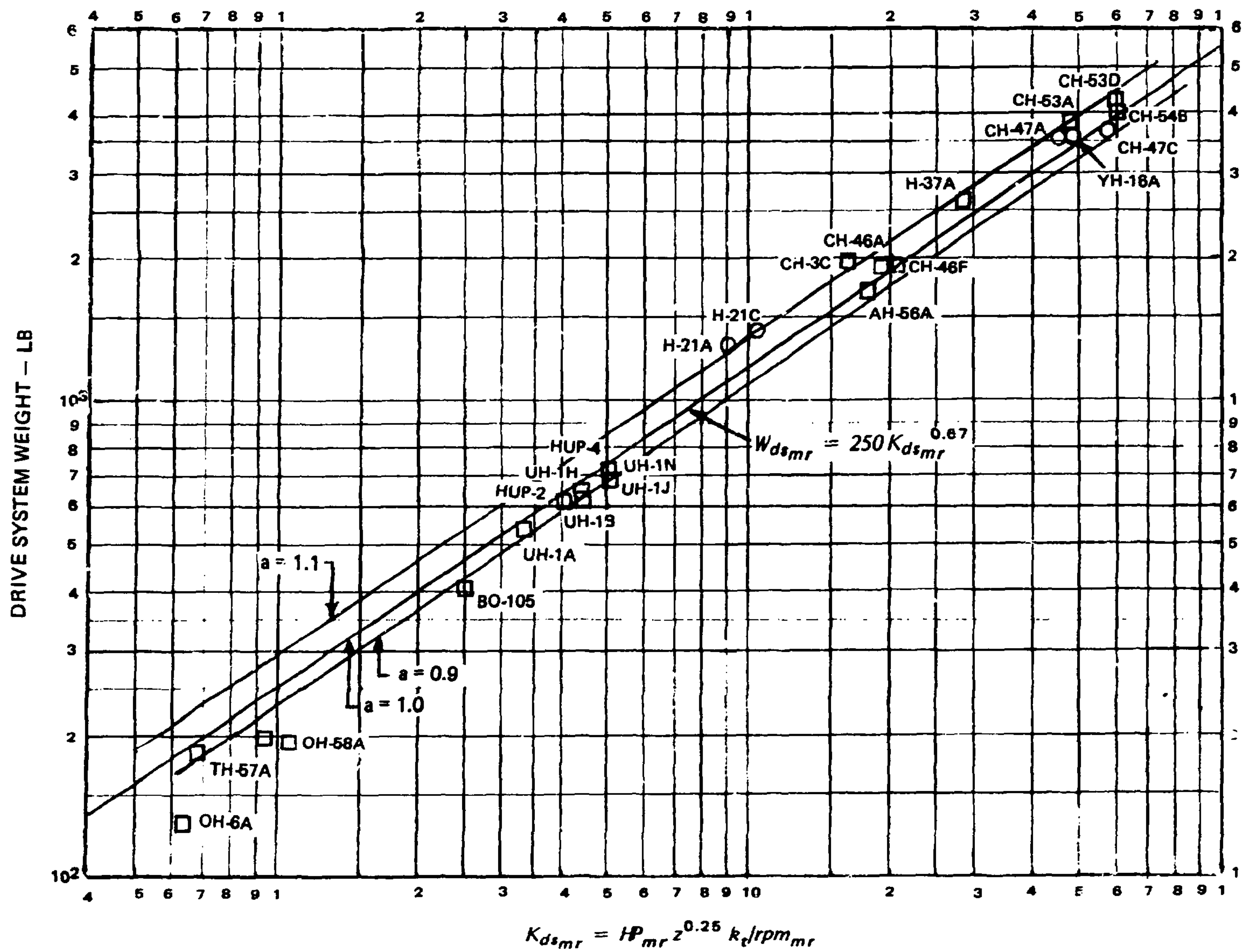


Figure 2.22 Drive system weight trend – primary and auxiliary

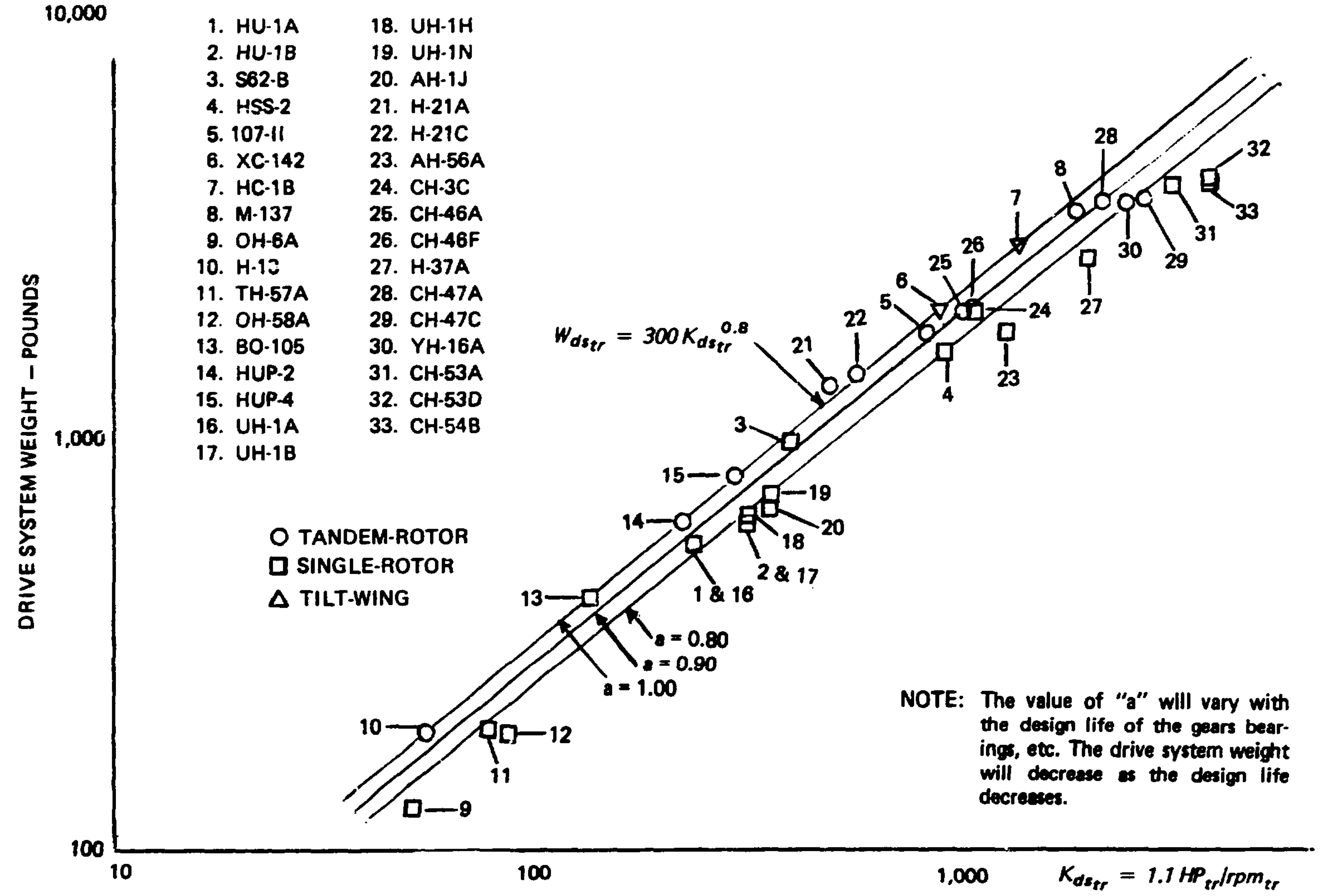


Figure 2.23 Tail-rotor drive-system weight trend

TABLE 2.6-BV

DRIVE SYSTEM WEIGHT ESTIMATES
FOR THREE HELICOPTER PAIRS

ITEM	HELICOPTER					
	UP TO 12,000 LB		12,000 TO 30,000 LB		30,000 TO 100,000 LB	
	Mi-2	BO-105	Mi-8	UH-60A	Mi-6	CH-53E
ACTUAL WEIGHT, LB	750.2	435.9	1987.3	1465.5	8410.2/8472.0	6257.1
BOEING VERTOL WEIGHT FORMULA	$W_{ds} = (W_{ds})_{mr} + (W_{ds})_{tr} = 250a_{mr}[(HP_{mr}/rpm_{mr})z_{mr}^{0.25}k_t]^{0.67} + 300a_{tr}[1.1(HP_{tr}/rpm_{tr})]^{0.8}$					
PARAMETER	VALUES					
a_{mr}	1.0	1.0	1.0	1.0	1.0	1.0
HP_{mr} hp	720	690	2700	2685	12,350	12,480
rpm_{mr}	246	424	192	258	120	179
z_{mr}	2	2	3	3	4	4.5
k_t	1.0	1.0	1.0	1.0	1.0	1.0
$(W_{ds})_{mr}$ lb	576.6	389.1	1766.3		7033.2	5525.9
a_{tr}	0.9	0.9	0.9	0.9	0.9	0.9
HP_{tr} hp	[80]	[90]	[300]	[320]	[1300]	[1360]
rpm_{tr}	1450	2220	1130	1214	675	699
$(W_{ds})_{tr}$ lb	28.7	22.4				
COMPUTED WEIGHT, lb	605.3	411.6	1893.3	1455.1	7555	6062.6
PREDICTED TO ACTUAL WEIGHT RATIO	0.81	0.94	0.95	0.995	0.90/0.89	0.94

RTL. Similar to the Tishchenko and Boeing-Vertol approaches, the ratios of power transmitted through various drive-system elements and the corresponding rpm serve as a basis for the weight estimates which is divided into separate predictions of the gearbox and shaft weights. However, the actual formulae are quite different from those of Tishchenko and Boeing Vertol. The combined weight of the system gearboxes (in pounds) is expressed as

$$W_{gb} = 172.7\, T_{mr_{gb}}^{0.7693}\, T_{tr_{gb}}^{0.079}\, n_{gb}^{0.1406} \tag{2.36}$$

where $T_{mr_{gb}} \equiv HP_{xm_{mr}} / rpm_{mr}$ is the ratio of the transmission rating in hp to the main-rotor rpm; $T_{tr_{gb}} \equiv 100(HP_{tr}/rpm_{tr})/T_{mr_{gb}}$ is the ratio of the tail-rotor power in hp to its rpm referred to as $T_{mr_{gb}}$; and n_{gb} is the number of gearboxes.

The weight in lb of the drive-shafts is given in the RTL approach as

$$W_{dsh} = 1.152\, T_{mr_{gb}}^{0.4266}\, T_{tr_{gb}}^{0.0709}\, L_{dr}^{0.8829}\, n_{dsh}^{0.3449} \tag{2.37}$$

where the new symbol L_{dr} is the horizontal distance in ft between the rotor hubs (main to tail); and n_{dsh} is the number of drive shafts (excluding the rotor shaft).

The sum of Eqs (2.36) and (2.37) obviously represents the total drive-system weight:

$$W_{ds} = W_{gb} + W_{dsh} \tag{2.38}$$

The values of the parameters appearing in Eqs (2.36) and (2.37), the weights predicted by this equation, and their comparison with the actual weights of the compared helicopters are shown in Table 2.6-RTL.

In this table, the drive system weights of the medium and heavy helicopters are predicted quite well, with differences no larger than +10 to −11 percent. However, for the Mi-2 and BO-105 pair of light helicopters, the predicted weights are as much as 29 percent below the actual weight for the BO-105, and 20 percent below for the Mi-2.

Discussion. The predicted-to-actual weight ratios for the three pairs of compared helicopters are plotted in Fig. 2.24, where the average values of those ratios are also indicated, as well as the maximum deviations from those averages.

All three methods depicted in this figure tend to under-predict actual drive-system weights. In this respect, Tishchenko's approach, on the average, shows the strongest tendency toward low weight estimates, as the average value amounts to 0.87. The average value for the Boeing-Vertol and RTL methods is the same (0.92); however, the margins of deviations from the average are smaller (+7 to −11 percent) for the Boeing-Vertol approach than those for RTL (+18 to −21 percent).

TABLE 2.6-RTL

DRIVE SYSTEM WEIGHT ESTIMATES
FOR THREE HELICOPTER PAIRS

ITEM		HELICOPTER					
		UP TO 12,000 LB		12,000 TO 30,000 LB		30,000 TO 100,000 LB	
		Mi-2	BO-105	Mi-8	UH-60A	Mi-6	CH-53E
ACTUAL WEIGHT, LB		750.2	435.9	1987.3	1465.5	8410.2/8472.0	6257.1
RTL WEIGHT FORMULA		$W_{ds} = W_{gb} + W_{dsh} = 172.7 T_{mr_{gb}}^{0.7693} T_{tr_{gb}}^{0.079} n_{gb}^{0.1406} + 1.152 T_{mr_{gb}}^{0.4265} T_{tr_{gb}}^{0.0709} L_{dr}^{0.8829} n_{dsh}$					
PARAMETER		VALUES					
$T_{mr_{gb}}$	hp/rpm	2.93	1.63	14.06	10.41	102.92	69.72
$T_{mr_{gb}}$		1.88	2.49	1.88	2.53	1.87	2.79
n_{gb}		3.0	3.0	3.0	5.0	3.0	7.0
W_{gb}	lb	484.4	315.4	1618.7	1413.0	7482.9	6447.9
L_{dr}	ft	26.6	19.5	40.7	32.6	66.9	49.5
n_{dsh}		3.0	4.0	4.0	4.0	4.0	5.0
W_{dsh}	lb	50.4	33.6	158.2	116.9	854.7	413.5
COMPUTED WEIGHT, lb		534.8	349.0	1776.9	1529.6	8337.6	6861.4
PREDICTED TO ACTUAL WEIGHT RATIO		0.71	0.80	0.89	1.04	0.99	1.10

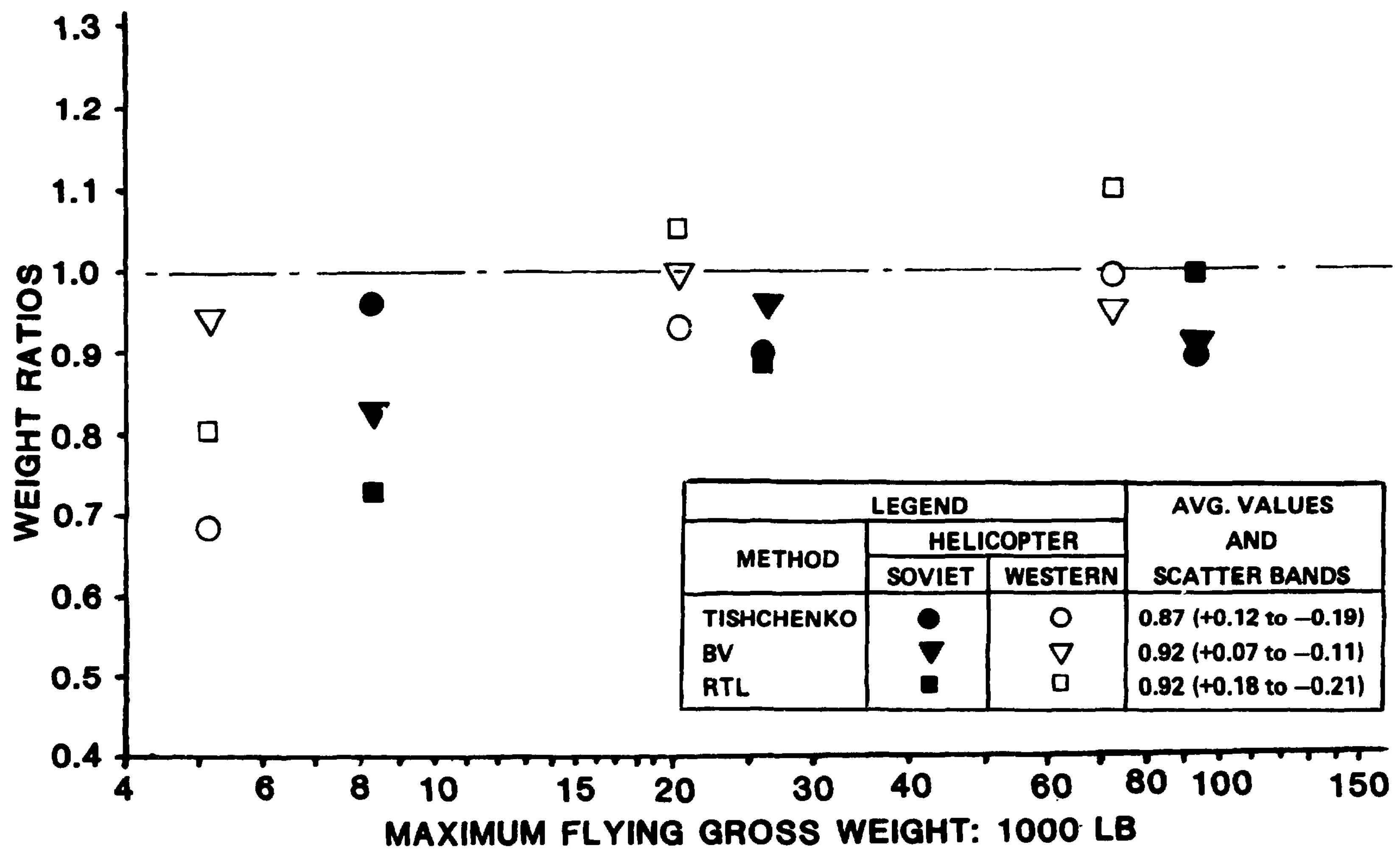


Figure 2.24 Predicted-to-actual weight ratios of drive systems

2.8 Fuel System

Tishchenko. In Ref. 1, the weight of the fuel system was determined as a fraction of the total fuel weight capacity $(W_{fu})_{tot}$:

$$W_{fs} = k_{fs}(W_{fu})_{tot} \tag{2.39}$$

where the value of the proportionality coefficient k_{fs} depends both on the helicopter configuration and the types of fuel tanks. Thus, for single-rotor helicopters with self-sealing fuel tanks, a coefficient of $k_{fs} = 0.07$ to 0.09 can be assumed. For systems without the self-sealing feature, this coefficient can be reduced to $k_{fs} = 0.06$ to 0.07.

For twin-rotor helicopters, the k_{fs} would be higher if the tanks were located far from the engines.

Since the structural weight of the integrated fuel tanks is usually included with that of the airframe, lower values of the weight coefficient ($k_{fs} \approx 0.035$ to 0.04) can be used.

The values of the k_{fs} coefficient for Soviet helicopters are shown in Fig. 2.25 which, in general, substantiates the k_{fs} levels discussed above. In Table 2.10[1], $k_{fs} = 0.09$ was shown; thus, the same value is assumed in the comparative calculations shown in Table 2.7-T where, in addition, the total fuel weight capacities are indicated.

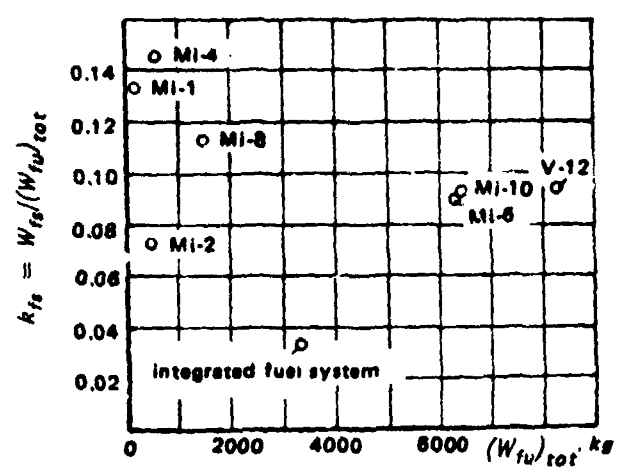


Figure 2.25 Weight coefficients of helicopter fuel systems

It can be seen from this table that the weight of the fuel system for the pair of small helicopters is overpredicted by about 24 percent for the Mi-2 and 35 percent for the BO-105 helicopters, if $k_{fs} = 0.09$ is assumed. By contrast, the fuel system weights for the two U.S. military helicopters (UH-60A and the CH-53E) are largely under-predicted by 48 and 40 percent, respectively, for the assumed k_{fs} value. This is probably because both helicopters have crash-resistant tanks, leading to relatively heavier structural weights.

TABLE 2.7-T

FUEL SYSTEM WEIGHT ESTIMATES
FOR THREE HELICOPTER PAIRS

ITEM	HELICOPTER					
	UP TO 12,000 LB		12,000 TO 30,000 LB		30,000 TO 100,000 LB	
	Mi-2	BO-105	Mi-8	UH-60A	Mi-6	CH-53E
ACTUAL WEIGHT, LB	79.9	67.6	361.3	429.1	1180.8	1225.0
TISHCHENKO WEIGHT FORMULA	$W_{fs} = k_{fs}(W_{fu})_{tot}$					
PARAMETER	VALUES					
k_{fs}; kg/kg	0.09	0.09	0.09	0.09	0.09	0.09
$(W_{fu})_{tot}$; kg	500	460	1460	1114.7	6200	3000
COMPUTED WEIGHT, kg	45.0	41.4	131.4	100.3	558.0	270.0
COMPUTED WEIGHT, lb	99.2	91.3	289.7	221.2	1230.4	595.5
PREDICTED TO ACTUAL WEIGHT RATIO	1.24	1.35	0.80	0.52	1.04	0.60

Boeing Vertol. As far as the general philosophy of determining the fuel-system weight is concerned, the Boeing-Vertol philosophy is the same as that of Tishchenko:

$$W_{fs} = k_{fs}(W_{fu})_{tot} \tag{2.40}$$

Also similar to Ref. 1, Ref. 2 gives the following instructions regarding the k_{fs} values: "For aircraft having simple fuel systems located in the fuselage sponsons or wing, the value for k_{fs} would range between 0.02 and 0.07; for aircraft requiring self-sealing tanks with more complex systems, the value would range between 0.10 and 0.15."

Following these instructions, the weight coefficient values were selected a priori as shown in Table 2.7-BV. In this table, the so-selected k_{fs} values resulted in a very good prediction of the fuel system weight (error < 6 percent) for the Mi-2, Mi-8, and CH-53E helicopters. However, for the remaining three helicopters, the prediction errors are much larger (between −20 and +27 percent).

RTL. The RTL philosophy of predicting the weight of the fuel system is different from that of Tishchenko and Boeing Vertol, as two separate equations are given; one for fuel tanks:

$$W_{ft} = 0.4341\, G_t^{0.7717}\, n_{ft}^{0.5897}\, F_{cr}^{0.393}\, F_{bs}^{1.9491} \tag{2.41}$$

and the other for the fuel system minus tanks:

$$W_{fs-t} = C_1 + C_2(0.01\, n_{ft} + 0.06\, n_{eng})FF_{max}^{0.866} \tag{2.42}$$

In Eq (2.41), G_t is the total fuel tank capacity in gallons; n_{ft} is the number of fuel tanks; F_{cr} is the fuel tank and supporting structure crashworthiness factor; and F_{bs} is the fuel tanks and supporting structure tolerance factor, which includes adjustments for (a) shielding by other components; (b) built-in ballistic tolerance; and (c) other peculiarities; for instance, beefed-up externally exposed tanks.

In Eq (2.42), C_1 is a constant accounting for such items in the fuel system as (a) auxiliary fuel system; (b) pressurization; (c) inflight refueling; (d) pressurized refueling, and other peculiarities; C_2 is a crashworthiness and survivability factor for the fuel system; n_{eng} is the number of engines; and FF_{max} is the maximum engine fuel flow in lb/hr.

Values of the parameters appearing in Eqs (2.41) and (2.42) are shown in Table 2.7-RTL, where the results of calculations are also given.

It can be seen from this table that Eqs (2.41) and (2.42) together, well predict the fuel system weights for the Mi-2 and UH-60A helicopters (errors: −1 and −8, respectively). For the BO-105, Mi-8, and CH-53E, the weight estimates become more erratic with errors amounting from about −17 to +29 percent. However, the worst performance of the RTL approach is registered for the Mi-6 case, where the weight of the fuel system is over-predicted by about 374 percent! This large error is probably the result on one hand, of the structure of Eqs (2.41) and (2.42) where the parameter representing the number of fuel tanks strongly influences the results; while on the other, resulting from an unusually

TABLE 2.7-BV

FUEL SYSTEM WEIGHT ESTIMATES
FOR THREE HELICOPTER PAIRS

ITEM	HELICOPTER					
	UP TO 12,000 LB		12,000 TO 30,000 LB		30,000 TO 100,000 LB	
	Mi-2	BO-105	Mi-8	UH-60A	Mi-6	CH-53E
ACTUAL WEIGHT, LB	79.9	67.6	361.3	429.1	1180.8	1225
BOEING VERTOL WEIGHT FORMULA	$W_{fs} = k_{fs} W_{fu}$					
PARAMETER	VALUES					
W_{fu} lb	1102.5	1014.3	3219.3	2458.0	13,671	6615
TYPE OF FUEL TANKS		B.T.	1 Int; 2 Ext	SS.CR	13 Int; 2 Ext	SS.CRC
k_{fs} lb/lb	0.07	0.07	0.11	0.14	0.11	0.14
COMPUTED WEIGHT, lb	77.2	71.0	354.1	344.1	1503.8	926.1
PREDICTED TO ACTUAL WEIGHT RATIO	0.97	1.16	0.98	0.80	1.27	0.94

NOTES: B.T. = Bladder Type; SS. = Self-Sealing; CR = Crash Resistant; CRC = Crash Resistant Cells.

TABLE 2.7-RTL

FUEL SYSTEM WEIGHT ESTIMATES
FOR THREE HELICOPTER PAIRS

ITEM	HELICOPTER					
	UP TO 12,000 LB		12,000 TO 30,000 LB		30,000 TO 100,000 LB	
	Mi-2	BO-105	Mi-8	UH-60A	Mi-6	CH-53E
ACTUAL WEIGHT, LB	79.9	67.6	361.3	429.1	1180.8	1225.0
RTL WEIGHT FORMULA	$W_{fs} = W_{ft} + W_{fs-t} = 0.4341\, G_t^{0.7717}\, n_{ft}^{0.5897} F_{cr}^{0.393} F_{bs}^{1.9491} + C_1 + C_2 (0.01 n_{ft} + 0.06 n_{eng}) FF_{max}^{0.866}$					
PARAMETER	VALUES					
G_t gal	166.5	153.5	492.0	362.0	3326.0	986.0
n_{ft}	3.0	3.0	3.0	2.0	13.0	4.0
F_{cr}	1.0	1.0	1.0	2.0	1.0	1.0
F_{bs}	[1.15]	1.0	2.0	2.0	2.0	1.5
W_{ft} lb	56.4	40.4	383	312.5	397.2	451.9
C_1 lb	0	0	0	0	0	248.3
C_2	1.0	1.0	1.5	2.0	1.5	2.0
n_{eng}	2	2	2	2	2	3
FF_{max} lb/hr	326.7	273.0	909.0	720.0	3515.0	2041.0
W_{fs-t} lb	22.6	19.6	82.0	83.5	442.0	571.7
COMPUTED WEIGHT, lb	79	60	465	396	4414	1023.6
PREDICTED TO ACTUAL WEIGHT RATIO	0.99	0.88	1.29	0.92	3.74	0.83

large number of fuel tanks (13, or even 15, counting the two external ones). It is apparent, hence, that in those cases where a large number of tanks are used in the fuel system, the RTL approach is not suitable for weight estimates of the fuel system.

Discussion. The ratios of the predicted to the actual weights of the fuel systems of the compared Soviet and Western helicopters are summarized in Fig. 2.26, where the average values and scatter bands are also shown. It can be seen from this figure that although the average values of the weight of Tishchenko (0.92) and Boeing Vertol (1.02) are reasonable, the scatter bands are quite large. This is especially true for the Tishchenko approach where deviations from the average as large as +0.213 and −0.40 are encountered. It should be remembered, however, that in this approach, a constant weight coefficient (k_{fs} = 0.09) was assumed across the board which resulted in gross weight under-estimates for fuel systems incorporating self-sealing, crash-resistant tanks (UH-60A and CH-53E).

The scatter band in the Boeing-Vertol approach, although still wide, is much narrower than for Tishchenko, as it amounts to +0.25 to −0.20.

When the Mi-6 is included in the comparison, then the RTL approach appears as the most erratic, since the average ratio of predicted to actual weight amounts to 1.44, and the scatter band extends up to +2.30 and goes down to −0.61. Should, however, the Mi-6 be excluded from the comparison, then the average ratio would be much better; amounting to 0.98, and the scatter band would be reduced (from +0.21 to −0.15).

It can be concluded, hence, that the Boeing-Vertol and Tishchenko approaches (based on the simple proportionality of fuel system weight to the total fuel-weight capacity) can be used for preliminary design estimates, provided that the values of the weight coefficients are properly selected to reflect design characteristics of the fuel tanks. The more elaborate RTL formula (in its present form) appears quite accurate as long as it is not applied to rotary-wing aircraft having more than 3 or 4 tanks.

2.9 Propulsion Subsystems

General. It is apparent from the ensuing considerations that the Tishchenko approach to weight predictions of the propulsion subsystem represents a different philosophy from that of Boeing Vertol and RTL. In the Soviet approach, powerplant rating is the only parameter on which weight-prediction is based. By contrast, in the Boeing-Vertol formula, the weight of the subsystem is assumed as simply proportional to the combined weight of the engines. The engine weight in the RTL treatment is retained as one of the parameters, but its influence is separated from that of the number of engines, and a special factor reflecting the design concept of the subsystem is added.

Tishchenko. 'Propulsion subsystems' is defined by Tishchenko as the powerplant installation system and includes the intake and exhaust systems, starting system, engine mounts, and the fire-extinguishing system. The expression for the weight of this system is given as follows:

$$W_{pss} = k_{pss}(SHP_{ref})_{tot} \tag{2.43}$$

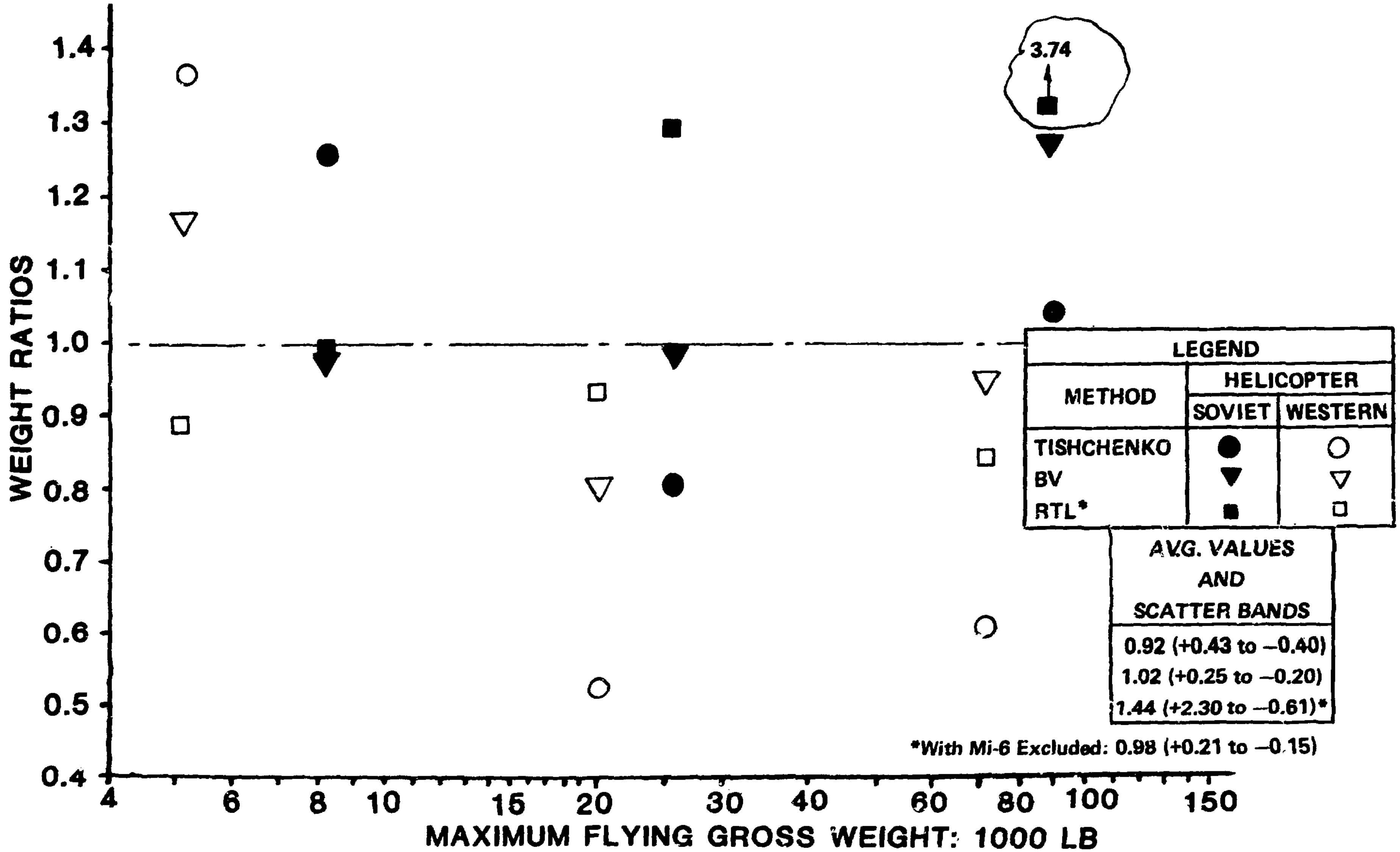


Figure 2.26 Predicted-to-actual weight ratios of fuel systems

where $(SHP_{ref})_{tot}$ is the total referred power (i.e., that available at an altitude of 500 m, ISA), and k_{pss} is the corresponding weight coefficient. Values of the k_{pss} coefficients for Soviet helicopters are shown in Fig. 2.27, where one would note the relatively small scatter of points for all the compared helicopters, with the exception of the Mi-2. The $0.04 < k_{pss} < 0.05$ values are recommended for weight predictions[1]. Consequently, $k_{pss} = 0.045$ will be used in this comparative study.

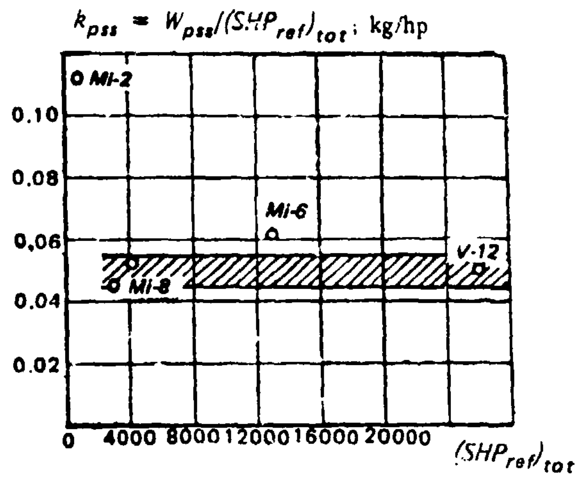


Figure 2.27 Weight coefficients of powerplant installation (hatched area corresponds to better (weight-wise) powerplant installations)

The actual propulsion subsystem weight estimates are shown in Table 2.8-T. When a constant weight coefficient value of 0.045 is used in this table, the proposed method generally under-estimates the propulsion subsystem weights for Soviet helicopters by about 59 percent for the Mi-2, and 28 percent for the Mi-6; and over-estimates (by as much as 99 percent for the CH-53E) for the Western counterparts. In view of these large and unpredictable discrepancies between the predicted and actual weights, it seems that the approach as represented by Eq (2.43) with a constant value of the k_{pss} coefficient is not very reliable.

Boeing Vertol. As previously mentioned, Boeing Vertol bases their estimate of the propulsion subsystem weight on the total weight of the engines:

$$W_{pss} = k_{pss}(n_{eng} W_{eng}) \tag{2.44}$$

As in the case of Tishchenko, the correlation between W_{pss} and $(n_{eng} W_{eng})$ is obtained through the weight coefficient k_{pss}, whose value of 0.22 was suggested by a representative of the Weights Group of Boeing Vertol.

It can be seen from Table 2.8-BV that using the fixed value of $k_{pss} = 0.22$ results in an under-prediction of the propulsion subsystem weights for the Mi-2, Mi-6, and CH-53E helicopters ranging

TABLE 2.8-T

PROPULSION SUBSYSTEM WEIGHT ESTIMATES
FOR THREE HELICOPTER PAIRS

ITEM	HELICOPTER					
	UP TO 12,000 LB		12,000 TO 30,000 LB		30,000 TO 100,000 LB	
	Mi-2	BO-105	Mi-8	UH-60A	Mi-6	CH-53E
ACTUAL WEIGHT, LB	198.5	56.5	297.7 458.6	143.0	1777.2	630.3
TISHCHENKO WEIGHT FORMULA	$W_{pss} = k_{pss}(SHP_{ref})_{tot}$					
PARAMETER	VALUES					
k_{pss}; kg/hp	0.045	0.045	0.045	0.045	0.045	0.045
$(SHP_{ref})_{tot}$	800	795	3030	2995	13,000[1]	12,615
COMPUTED WEIGHT, kg	36.0	35.8	136.3	134.8	585	567.6
COMPUTED WEIGHT, lb	79.38	78.9	300.7	297.2	1289.9	1251.7
PREDICTED TO ACTUAL WEIGHT RATIO	0.41	1.14	1.01 0.66	2.07	0.72	1.99

TABLE 2.8-BV

PROPULSION SUBSYSTEM WEIGHT ESTIMATES
FOR THREE HELICOPTER PAIRS

ITEM	HELICOPTER					
	UP TO 12,000 LB		12,000 TO 30,000 LB		30,000 TO 100,000 LB	
	Mi-2	BO-105	Mi-8	UH-60A	Mi-6	CH-53E
ACTUAL WEIGHT, LB	198.5	56.5	297.7/458.6	143.0	1777.2	630.3
BOEING VERTOL WEIGHT FORMULA	$W_{pss} = k_{pss} W_{eng}$					
PARAMETER	VALUES					
k_{pss} lb/lb	0.22	0.22	0.22	0.22	0.22	0.22
ΣW_{eng} lb	608	316	1454	830	5842	2160
COMPUTED WEIGHT, lb	133.8	69.5	320.5	182.6	1285.2	475.2
PREDICTED TO ACTUAL WEIGHT RATIO	0.67	1.23	1.08	1.28	0.72	0.75

from 33 to 25 percent; and an over-prediction by a margin of 8 to 20 percent for the Mi-8, BO-105, and UH-60A helicopters. However, when compared with the estimates shown in Table 2.8-T, the Boeing Vertol approach demonstrates a much narrower scatter of the ratios of predicted to actual values than in the Tishchenko case.

RTL. The RTL equation for estimating the weights of propulsion subsystems is as follows:

$$W_{pss} = 2.0088\, W_{eng}^{\;0.5979}\, n_{eng}^{\;0.7858}\, (F_{lo})^{0.5655} \tag{2.45}$$

In this equation it can be seen that although the propulsion subsystem weight depends on engine weight and the number of engines, this relationship is not expressed in a linear manner as in the case of Boeing Vertol. Furthermore, an additional correction factor (F_{lo}), reflecting the design concept is added. Namely, when the lubricating oil system is integral with the engines, then F_{lo} = 1.0, and when it is external, then F_{lo} = 2.0.

In Table 2.8-RTL, it can be seen that Eq (2.45) generally tends to under-predict the propulsion subsystem weights. However, there is an exception to this trend, as shown by the BO-105, where the estimated weight is 87 percent higher than the actual weight.

Discussion. The predicted to actual weight ratios computed in Tables 2.8-T, 2.8-BV, and 2.8-RTL are summarized in Fig. 2.28. A glance at this figure would indicate that the Boeing-Vertol approach, although far from ideal (scatter band from +0.32 to −0.29) still appears as the most reliable of the three compared approaches. This is because the average value in the Tishchenko method is high (1.22), and the scatter bands are quite wide (+0.98 to −0.55); while in the RTL case, even though the average value is low (0.89), the scatter band (from +0.98 to −0.55) is almost as wide as that of Tishchenko.

2.10 Flight Control Group

General. In all of the three approaches considered here, some distinct contributions to the total flight-control group weight are estimated separately. Thus, in Ref. 1, separate computations are performed for the manual portion from that representing boosted controls. The Boeing-Vertol procedure distinguishes the weights of cockpit, main-rotor, and systems controls plus hydraulics. Finally, in the RTL approach, the weights of cabin and other flight controls are estimated separately. The gross weight of the aircraft appears as a parameter in weight equations in the Boeing-Vertol and RTL formulae. In addition, the weight (thrust) per rotor and blade weight are also considered as parameters by Boeing Vertol. In the Tishchenko approach, neither the gross weight of the aircraft nor the thrust per rotor appear in the control weight equations. The main-rotor radius, blade chord, and number of blades are all present in the weight equations of Tishchenko and Boeing Vertol. However, of the three quantities, only the blade chord is included in the RTL equations.

It can be seen, hence, that there are distinct differences in the three considered methods regarding the basic philosophy of what constitutes an important parameter in flight control weight estimates.

TABLE 2.8-RTL

PROPULSION SUBSYSTEM WEIGHT ESTIMATES
FOR THREE HELICOPTER PAIRS

ITEM	HELICOPTER					
	UP TO 12,000 LB		12,000 TO 30,000 LB		30,000 TO 100,000 LB	
	Mi-2	BO-105	Mi-8	UH-60A	Mi-6	CH-53E
ACTUAL WEIGHT, LB	198.5	56.5	297.7/458.6	143.0	1777.2	630.3
RTL WEIGHT FORMULA	$W_{pss} = 2.0088\, W_{eng}^{0.5979}\, n_{eng}^{0.7858}\, F_{lo}^{0.5655}$					
PARAMETER	VALUES					
W_{eng} lb	304	158	727	415	2921	720
n_{eng}	2	2	2	2	2	3
F_{lo}	2.0	2.0	2.0	1.0	2.0	2.0
COMPUTED WEIGHT, lb	156.4	105.8	263.4	127.3	605.0	360.2
PREDICTED TO ACTUAL WEIGHT RATIO	0.79	1.87	0.88	0.89	0.34	0.57

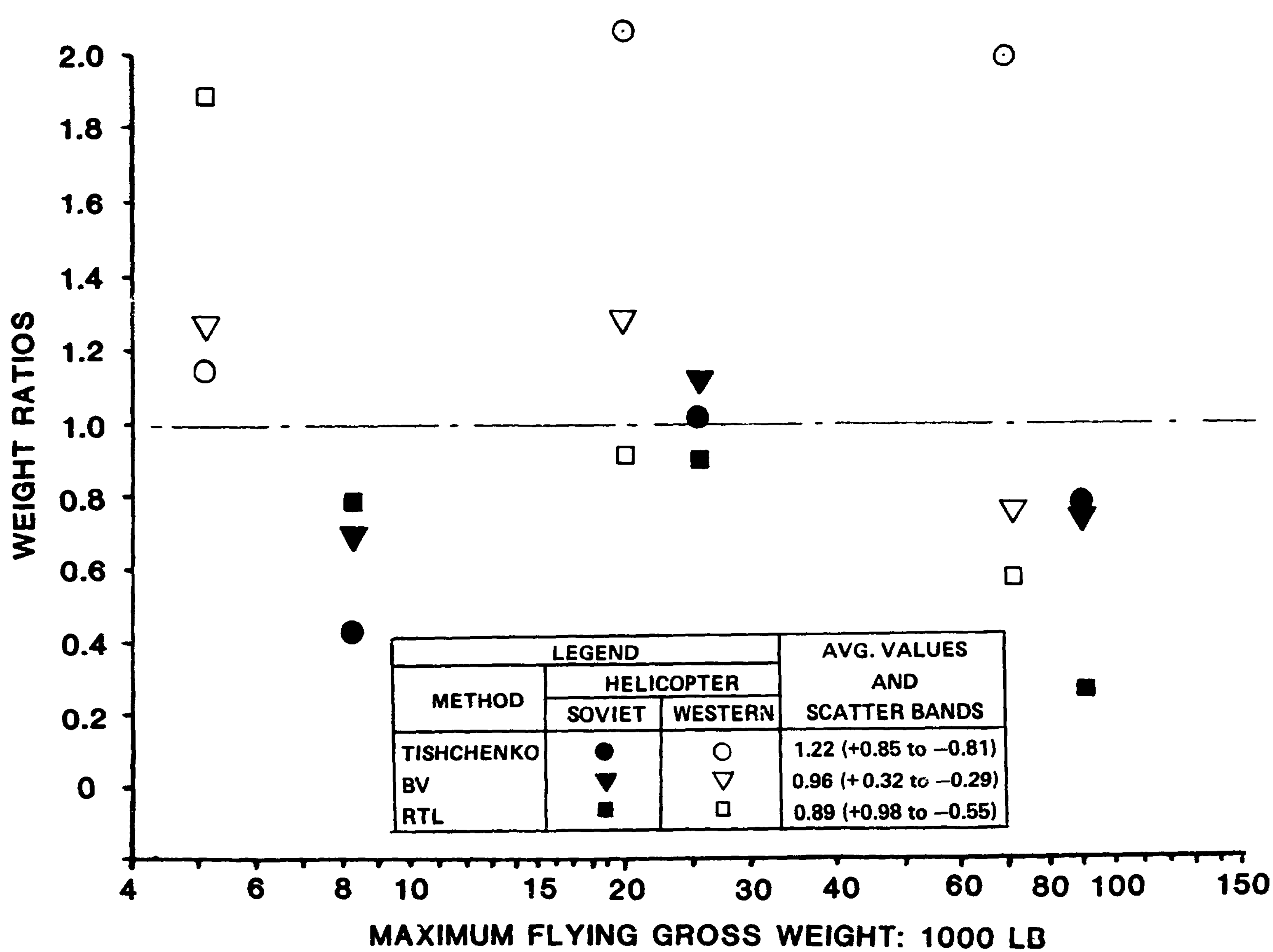


Figure 2.28 Predicted-to-actual weight ratios of propulsion subsystems

Tishchenko. In Table 2.10 of Ref. 1, flight control weight is computed by separately estimating the weight of boosted (W_{bc}) and manual (W_{mc}) controls. The first of the above includes the weights of the swashplates, booster controls, and the hydraulic system of lifting rotors, and is expressed as follows:

$$W_{bc} = k_{bc} n_{bl} c^2 R \tag{2.46}$$

where k_{bc} is the weight coefficient covering all of the above-mentioned items.

The weight coefficients of boosted control assemblies of several Soviet helicopters are shown in Fig. 2.29, which also shows the contributions of the swashplate to the assembly. It should be noted that the scatter of all the points shown is relatively small, as their values are included within a band of $16.0 < k_{bc} < 20.0$. However, in more modern designs, lower control weights may be achieved.

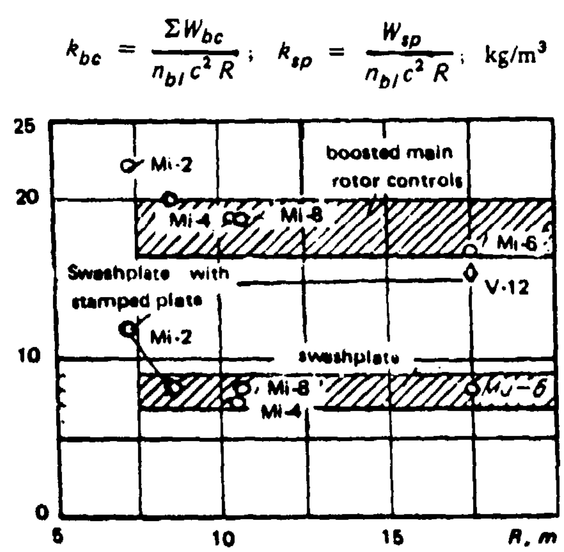


Figure 2.29 Weight coefficient of boosted controls and swashplates

In the study of hypothetical helicopters depicted in Table 2.10[1], $k_{bc} = 13.2$ is used for all the considered configurations, and this value will also be adapted in this comparison study.

For manual controls, the following formula is given for single-rotor configurations[1]:

$$W_{mc} = k_{mc} R \tag{2.47}$$

where the suggested value of the weight coefficient is $k_{mc} = 25$. Statistical support for this value is given in Fig. 2.30.

For twin-rotor types, the main-rotor blade radius (R) is replaced in Eq (2.47) by the distance (L) between the lifting rotors:

$$W_{mc} = k_{mc} L \tag{2.47a}$$

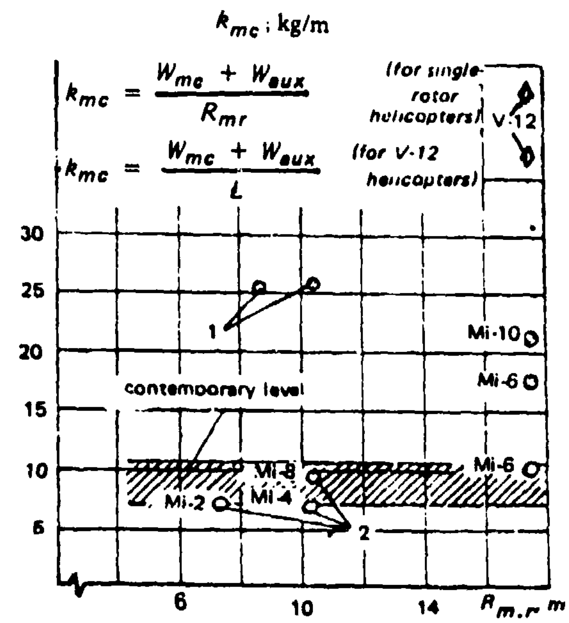


Figure 2.30 Weight coefficients of manual (preboost) controls; (1) helicopters with retractable L/G, and (2) helicopters without auxiliary control systems (hatched symbols refer to weight coefficients of manual and auxiliary controls,

where k_{mc} = 30 and k_{mc} = 35 is proposed for the tandem and side-by-side types, respectively. It should be emphasized, however, that all of the above indicated k_{mc} values refer to controls actuating the cargo doors, entry ladders, cowlings, and landing-gear retraction. For simpler controls, the values indicated by the hatched area in Fig. 2.30 may be expected. Consequently, for the first two helicopters in Table 2.9-T, k_{mc} = 1 will be used, while for the rest, k_{mc} = 25 (as shown in Table 2.10[1]) will be applied.

Inputs needed for flight-control estimates and predicted weights are shown in Table 2.9-T. One can see from this table that except for the CH-53E, all other flight control weights were under-estimated. This margin of under-estimate varies from 36 percent for the Mi-6 to only 6 percent for the Mi-8. Over-estimate for the CH-53E amounts to 21 percent.

Boeing Vertol. In the Boeing Vertol approach[2], the following three contributions to the overall flight control group are distinguished: (a) cockpit control weight (W_{cc}), (b) main-rotor control weight (W_{mrc}), and (c) the weight of the rotor system controls (including hydraulics) (W_{rsc}). Separate equations are given for each item:

$$W_{cc} = k_{cc}(10^{-3}\, W_{gr})^{0.41} \quad (2.48)$$

where W_{gr} is the design gross weight, and the suggested value of the weight coefficient is k_{cc} = 26, while the exponent for the $(10^{-3} W_{gr})$ term is 0.41.

TABLE 2.9-T

FLIGHT CONTROL GROUP WEIGHT ESTIMATES
FOR THREE HELICOPTER PAIRS

ITEM	HELICOPTER					
	UP TO 12,000 LB		12,000 TO 30,000 LB		30,000 TO 100,000 LB	
	Mi-2	BO-105	Mi-8	UH-60A	Mi-6	CH-53E
ACTUAL WEIGHT, LB	350.1	217.9	1068.6	834.5	5479.4	1656.1
TISHCHENKO WEIGHT FORMULA	$W_{fc} = W_{bc} + W_{mc} = k_{bc} n_{bl} c^2 R + k_{mc} R$					
PARAMETER	VALUES					
k_{bc}	13.2	13.2	13.2	13.2	13.2	13.2
n_{bl}	3	4	5	4	5	7
c; m	0.40	0.27	0.52	0.53	1.00	0.74
R; m	7.25	4.92	10.65	8.18	17.5	12.04
W_{bc}; kg	45.9	18.9	190.1	121.3	1155.0	709.2
k_{mc}	25	25	25	25	25	25
R; m	7.25	4.92	10.65	8.18	17.50	12.04
W_{mc}; kg	181.2	123.0	266.25	204.5	437.5	301.0
COMPUTED WEIGHT, kg	227.1	141.9	456.3	325.8	1592	910.2
COMPUTED WEIGHT, lb	500.8	313.0	1006.2	718.4	3510.4	2007.0
PREDICTED TO ACTUAL WEIGHT RATIO	1.43	1.44	0.94	0.86	0.64	1.21

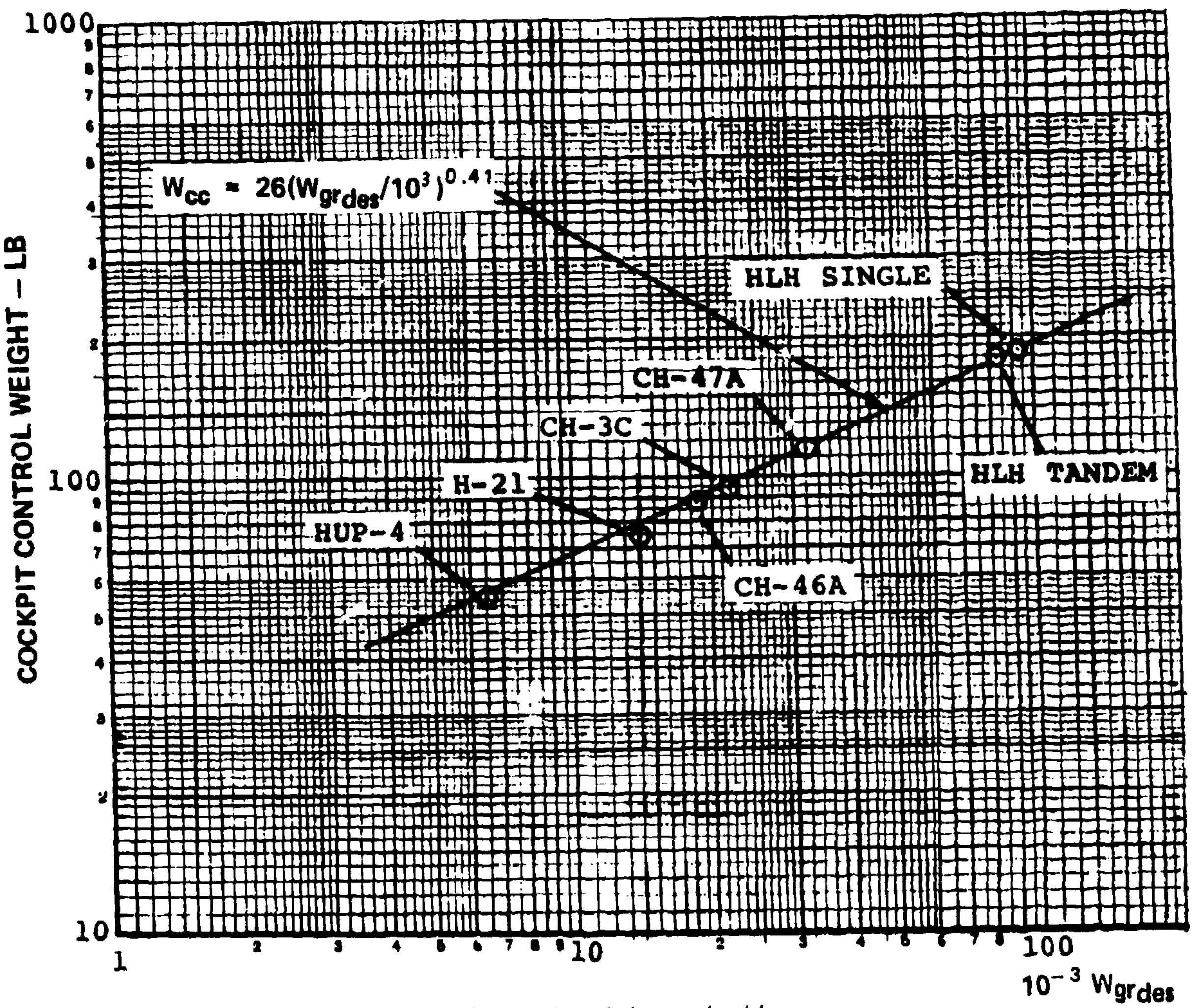


Figure 2.31 Cockpit control weights

Statistical substantiation for Eq (2.48) and the numerical values indicated above are shown in Fig. 2.31.

$$W_{mrc} = k_{mrc}[c(R\,n_{bl}\,W_{bl}\,10^{-3})^{0.5}]^{1.1} \tag{2.49}$$

where a new parameter under the form of blade weight (W_{bl}) is incorporated. With the weight coefficient $k_{mrc} = 26$, and various exponent values as indicated in Eq (2.49), a good correlation of predicted and actual weights is obtained (Fig. 2.32).

$$W_{rsc} = k_{rsc}(10^{-3}\,W_{pmr})^{0.84} \tag{2.50}$$

where W_{pmr} is the helicopter gross weight per rotor – for a single-rotor helicopter, this would obviously be identical to the aircraft gross weight, and k_{rsc} is the weight coefficient having a suggested value of 30.

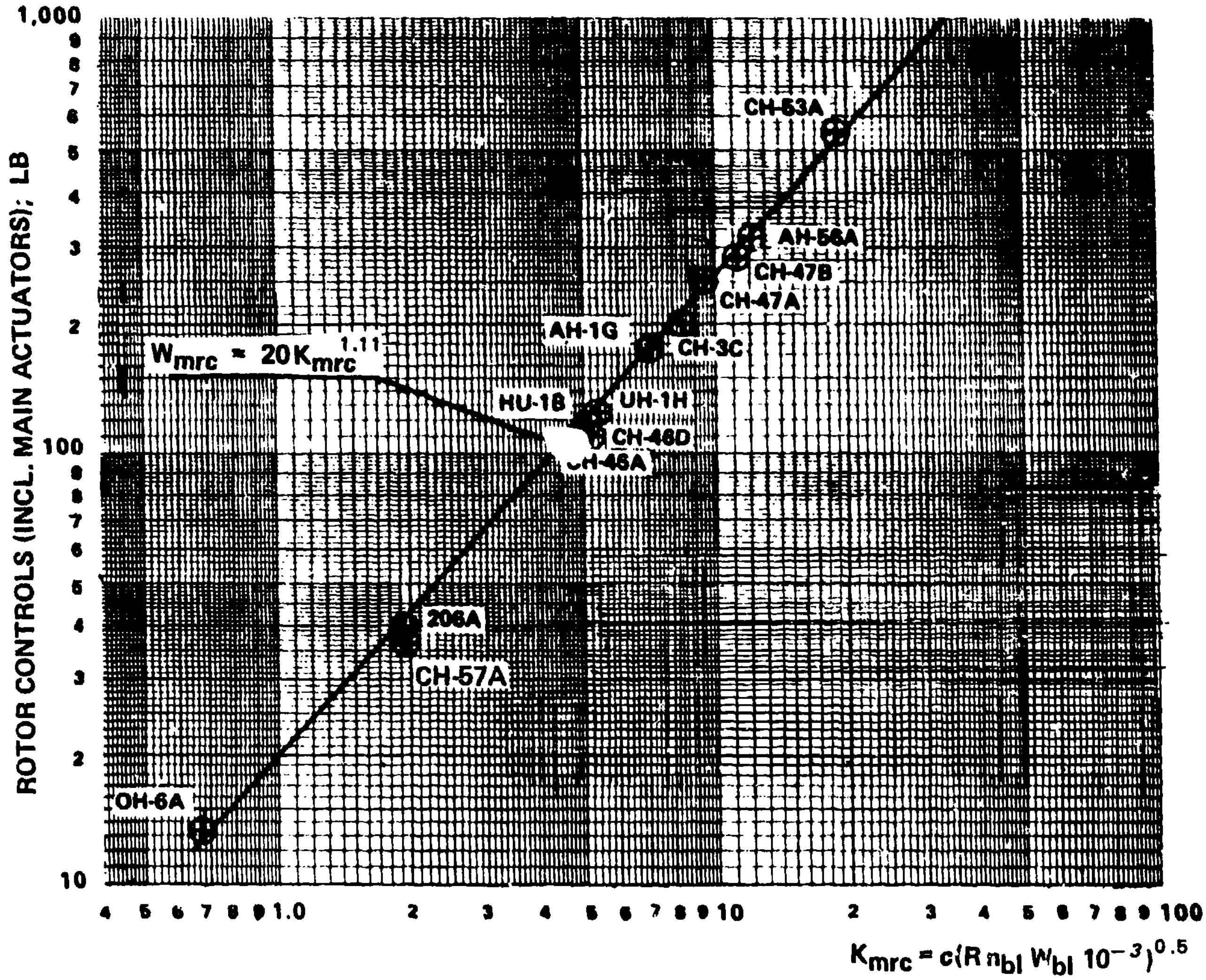


Figure 2.32 Weight of rotor controls plus main actuators

Statistical substantiation for Eq (2.50) is shown in Fig. 2.33.

The total flight control group weight will obviously be obtained as the sum of Eqs (2.48) through (2.50).

$$W_{fc} = W_{cc} + W_{mrc} + W_{rsc} \tag{2.51}$$

The parametric values and calculations related to the above weight equations are given in Table 2.9-BV.

It can be seen from this table that the selection of the design gross weight as the W_{gr} parameter generally leads to an under-prediction of the control system weight. The CH-53E represents an exception

TABLE 2.9-BV

FLIGHT-CONTROL GROUP WEIGHT ESTIMATES
FOR THREE HELICOPTER PAIRS

ITEM	HELICOPTER					
	UP TO 12,000 LB		12,000 TO 30,000 LB		30,000 TO 100,000 LB	
	Mi-2	BO-105	Mi-8	UH-60A	Mi-6	CH-53E
ACTUAL WEIGHT, LB	350.1	217.9	1068.6	834.5	5479.4	1658.1
BOEING VERTOL WEIGHT FORMULA	$W_{fc} = k_{cc}(10^{-3} W_{gr_{des}})^{0.41} + k_{mrc}[c(R\, n_{bl}\, W_{bl}\, 10^{-3})^{0.5}]^{1.11} + k_{rsc}\,(10^{-3} W_{pmr})^{0.84}$					
PARAMETER	VALUES					
k_{cc}	26	26	26	26	26	26
W_{gr} lb	8158	4442/6300	24,255	16,835	90,405	56,000
k_{mrc}	2.0	2.0	2.0	2.0	2.0	2.0
c ft	1.312	0.89	1.71	1.73	3.28	2.44
R ft	23.88	16.14	34.94	26.83	57.42	39.50
n_{bl}	3	4	5	4	5	7
W_{bl} lb	121.33	67.05	255.8/295.4	210.3	1553.8/1190.2	412.1
k_{rsc}	30	30	30	30	30	30
W_{pmr} lb	8158	4442/6300	24,255	16,835	90,405	56,000
COMPUTED WEIGHT, lb	325.0	192.7/235.9	824.6/848.7	600	3600.8/3309.7	1765.1
PREDICTED TO ACTUAL WEIGHT RATIO	0.93	1.02/1.25	0.77/0.79	0.72	0.66/0.60	1.06

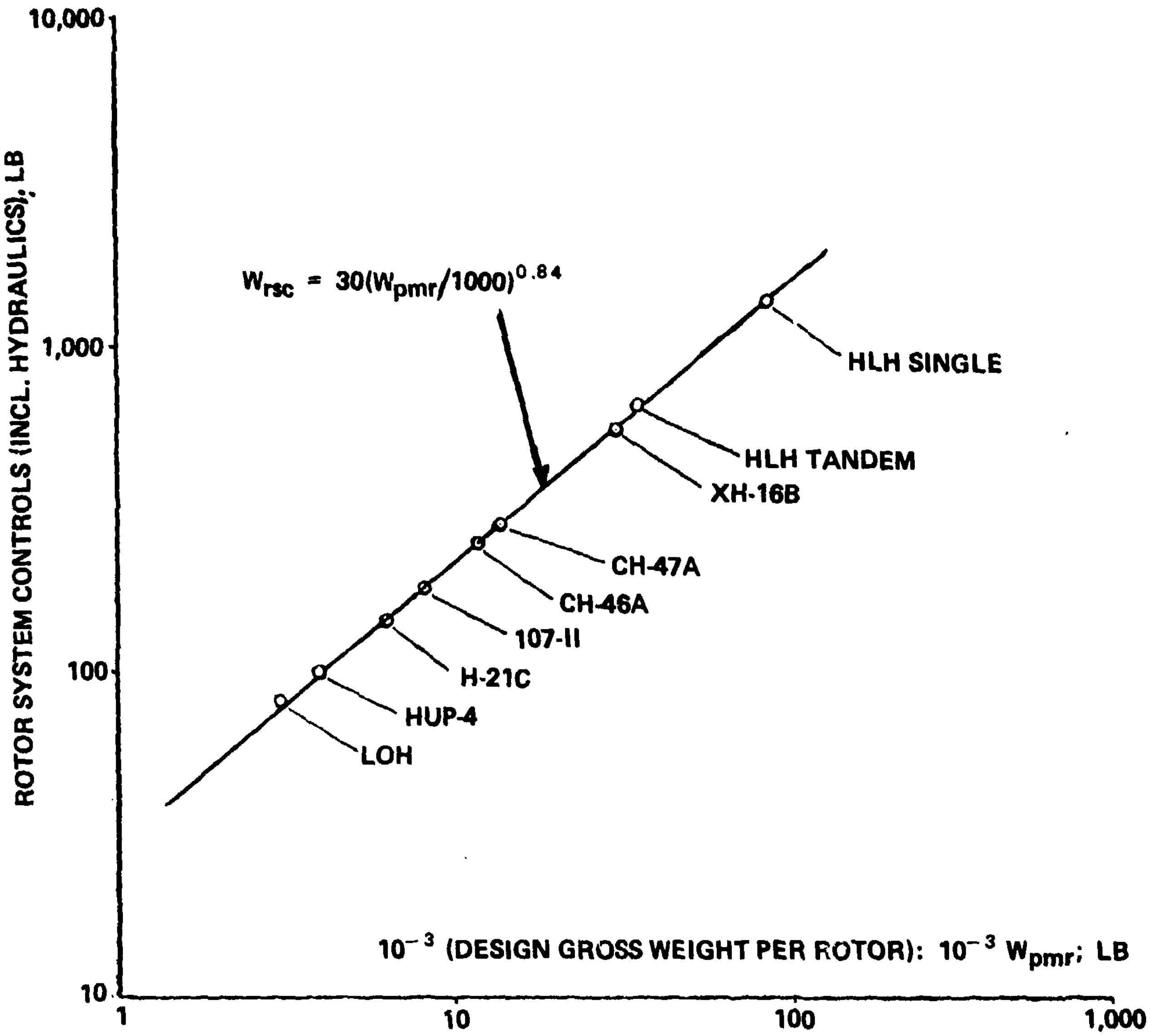


Figure 2.33 Rotor system controls and hydraulics weight trend

to the rule, since using its design gross weight of 50,000 lb, a good correlation with the actual gross weight is obtained. Should, as in the case of the BO-105, its maximum gross weight of 5114 lb be used instead of the 4442 lb representing the design gross weight, then the predicted weight of the flight control group would amount to 208.8 lb with a corresponding ratio of predicted to actual weights equal to 0.95.

RTL. The weight of the cockpit controls for the RTL approach is given as follows:

$$W_{cc} = 0.0985(F_{cp})^{0.3368}\,(W_{gr})_{max}{}^{0.7452}/(F_{cb})^{1.1125} \tag{2.52}$$

where F_{cp} is the flight control ballistic tolerance coefficient (no = 1.0; yes = 2.0). The gross weight in this equation should correspond to its maximum flying value, and F_{cb} is a coefficient having a value of 1.0 for the mechanical-type controls, and 2.0 for boosted-type controls.

The weight of the rotating and nonrotating flight controls (W_{rfc}) is expressed as:

$$W_{rfc} = 0.1657(F_{cb})^{1.3696} c^{0.4481} F_{cp}^{0.4469} (W_{gr})_{max}^{0.6865} \tag{2.53}$$

where the new symbol is c (blade chord in ft).

The total weight of the flight control group is obtained by summing Eqs (2.52) and (2.53):

$$W_{fc} = W_{cc} + W_{rfc} \tag{2.54}$$

Calculations related to this equation are shown in Table 2.9-RTL. It can be seen from this table that in this case, the RTL method tends to consistently under-predict flight control group weights. The smallest errors are for the CH-53E and UH-60A, where they amount to −4 and −8 percent, respectively; while the largest is for the Mi-6, where the predicted weight is off by −61 percent.

Discussion. The ratios of predicted-to-actual flight control group weights are plotted in Fig. 2.34, where the average values and scatter bands are also shown. A glance at this figure would indicate that all three of the discussed approaches greatly under-predict the control group weight of the Mi-6. This may signify that the controls of this helicopter are exceptionally heavy, and out-of-line from the general trend.

By excluding the Mi-6 from the comparison (see the last column of average values in Fig. 2.34), both the average values and width of the scatter bands improve, but the tendency for under-prediction still remains visible in all three methods. With respect to accuracy, it looks that the Boeing Vertol approach is slightly better than the other two.

2.11 Summary Weights of Major Components

Comparison of Summary Weights. For each pair of the considered Soviet and Western helicopters, the previously predicted major component weights are summarized in Tables 2.10 (Mi-2—BO-105), 2.11 (Mi-8—UH-60A), and 2.12 (Mi-6—CH-53E), along with the actual weights. In the last row of each table referring to a particular helicopter, a summary of the actual weights and those predicted by the three investigated weight methods are given. Note that two sets of summary weights are often given since, in some cases, the actual and computed weights represent both lighter and heavier components. The corresponding ratios of the predicted to actual summary weights are also shown in the last rows and plotted in Fig. 2.35 where, in addition, the average values of the ratios and scatter bands are also indicated.

Mi-2 – BO-105 Pair

Mi-2. Looking at the upper part of Table 2.10, one will find that the actual summary weight of the major components of the Mi-2 helicopter considered here amounts to 3298.1 lb.

TABLE 2.9-RTL

FLIGHT CONTROL GROUP WEIGHT ESTIMATES
FOR THREE HELICOPTER PAIRS

ITEM	HELICOPTER					
	UP TO 12,000 LB		12,000 TO 30,000 LB		30,000 TO 100,000 LB	
	Mi-2	BO-105	Mi-8	UH-60A	Mi-6	CH-53E
ACTUAL WEIGHT, LB	350.1	217.9	1068.6	834.5	5479.4	1658.1
RTL WEIGHT FORMULA	$W_{fc} = W_{cc} + W_{rfc} = 0.0985(F_{cp})^{0.3368}(W_{gr})_{max}^{0.7452}/(F_{cb})^{1.1125} + 0.1657(F_{cb})^{1.3696} c^{0.4481} (F_{cp})^{0.4469} (W_{gr})_{max}^{0.6865}$					
PARAMETER	VALUES					
F_{cp}	1.0	1.0	1.0	2.0	1.0	1.0
$(W_{gr})_{max}$ lb	8175	5114	26,455	20,250	93,700	73,500
F_{cb}	2.0	2.0	2.0	2.0	2.0	2.0
W_{cc} lb	37.5	26.4	89.2	93.1	230.9	191.0
c ft	1.31	0.89	1.71	1.73	3.28	2.44
W_{rfc} lb	234.5	142.9	591.7	674.8	1886.7	1399.3
COMPUTED WEIGHT, lb	272.0	169.3	680.9	767.9	2117.6	1590.3
PREDICTED TO ACTUAL WEIGHT RATIO	0.78	0.78	0.64	0.92	0.39	0.96

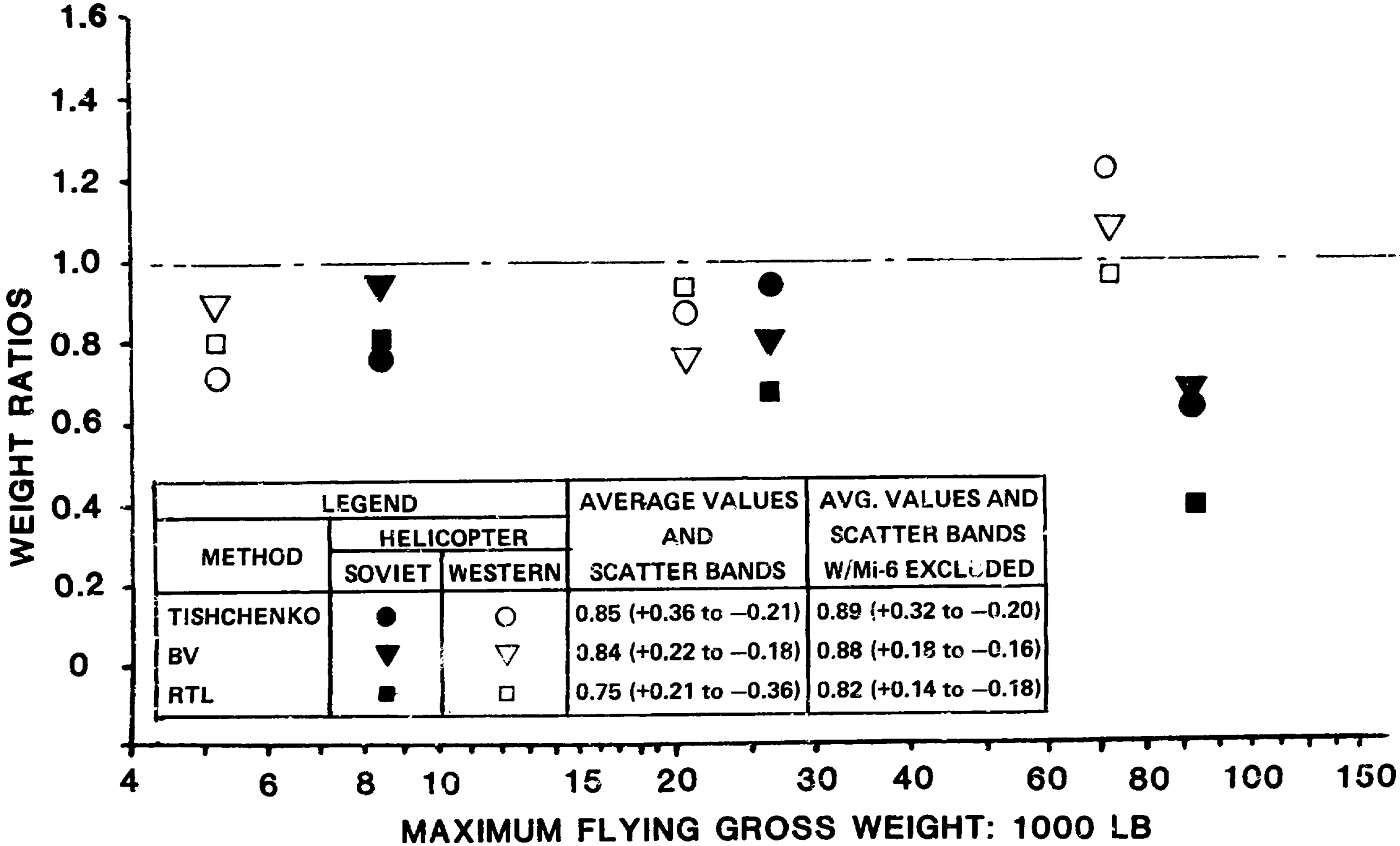


Figure 2.34 Predicted-to-actual weight ratios of flight control groups

TABLE 2.10

WEIGHT SUMMARY
FOR THE UP TO 12,000-LB GROSS-WEIGHT PAIR

ITEM	ACTUAL WEIGHT	METHOD					
		TISHCHENKO		BOEING VERTOL		RES. & TECH. LABS	
	W_a; lb	W_p; lb	W_p/W_a	W_p; lb	W_p/W_a	W_p; lb	W_p/W_a
HELICOPTER	Mi-2						
1. Main-Rotor Blades	363.8	333.8 367.6	0.92 1.00	352.2	0.97	363.8	1.06
2. Main-Rotor Hubs	291.1	256.4	0.88	187.5	0.64	294.5	1.01
3. Tail-Rotor Group	54.9	67.1	1.26	31.6	0.59	39.7	0.74
4. Fuselage	981.2	850.5	0.87	940.8	0.96	1028.8	1.05
5. Landing Gear	228.4	163.2	0.74	244.7	1.07	276.8	1.21
6. Drive System	750.2	719.7	0.96	605.3	0.81	534.8	0.71
7. Fuel System	79.9	99.2	1.24	77.2	0.97	79.0	0.99
8. Propulsion Subsystem	198.5	79.4	0.41	133.8	0.67	156.4	0.79
9. Flight Control Group	350.1	500.8	1.43	325.0	0.93	272.0	0.78
Σ (1...9)	3298.1	3069.1 3102.9	0.93 0.94	2898.1	0.88	3045.8	0.92
HELICOPTER	BO-105						
1. Main-Rotor Blades	268.2	153.3 198.0	0.57 0.74	238.3	0.89	257.7	0.96
2. Main-Rotor Hubs	200.5	403.5	2.00	175.0 184.5	0.86 0.91	186.2	0.93
3. Tail-Rotor Group	21.9	45.5	2.08	23.4	1.06	15.8	0.72
4. Fuselage	657.3	559.6 579.7	0.85 0.88	670.4	1.02	606.7 640.7	0.92 0.97
5. Landing Gear	104.2	44.4	0.43	66.6 94.5	0.64 0.91	71.6	0.69
6. Drive System	435.9	296.4	0.68	411.6	0.94	349.0	0.80
7. Fuel System	67.6	91.3	1.35	71.0	1.16	60.0	0.88
8. Propulsion Subsystem	56.5	78.9	1.14	69.5	1.23	105.8	1.8[illegible]
9. Flight Control Group	217.9	313.0	1.44	192.7 235.9	1.02 1.25	169.3	0.78
Σ (1...9)	2030.0	1986.9 2050.7	0.98 1.01	1918.5 1999.1	0.95 0.98	1822.1 1856.1	0.90 0.91

TABLE 2.11

WEIGHT SUMMARY
FOR THE 12,000 – 30,000-LB GROSS-WEIGHT PAIR

ITEM	ACTUAL WEIGHT	METHOD					
		TISHCHENKO		BOEING VERTOL		RES. & TECH. LABS	
	W_a; lb	W_p; lb	W_p/W_a	W_p; lb	W_p/W_a	W_p; lb	W_p/W_a
HELICOPTER	Mi-8						
1. Main-Rotor Blades	1278.9 1477.4	1298.1	1.02 0.88	1300.9	1.02 0.88	1273.6	1.00 0.87
2. Main-Rotor Hubs	1333.0	1283.9	0.96	938.3 988.1	0.70 0.74	1401.2	1.05
3. Tail-Rotor Group	150.0 259.3	155.8 351.5	1.04 1.36	125.8	0.84 0.49	142.6 143.7	0.95 0.55
4. Fuselage	3230.3	1774.6	0.86	2889.2	0.90	4046.4	1.25
5. Landing Gear	685.3	485.1	0.71	727.6	1.06	644.0	0.94
6. Drive System	1987.3	1773.5	0.89	1893.3	0.95	1776.9	0.89
7. Fuel System	361.3	289.7	0.80	354.1	0.98	465.0	1.29
8. Propulsion Subsystem	297.7 458.6	300.7	1.01 0.66	320.5	1.08	263.4	0.88
9. Flight Control Group	1068.6	1006.2	0.94	824.6 848.7	0.77 0.79	680.9	0.64
Σ (1...9)	10,392.4 10,861.1	9367.6 9563.3	0.91 0.88	9374.3 9448.2	0.90 0.87	10,694.0 10,695.1	1.03 0.98
HELICOPTER	UH-60A						
1. Main-Rotor Blades	841.1	836.4 909.1	0.99 1.08	782.4	0.93	774.3	0.92
2. Main-Rotor Hubs	605.9	953.2	1.57	601.6	0.99	641.1	1.06
3. Tail-Rotor Group	122.9	186.6	1.52	108.7	0.88	103.1	0.84
4. Fuselage	2284.0	2212.5	0.98	2415.2	1.06	2252.4	0.99
5. Landing Gear	457.6	329.0	0.72	505.0	1.10	531.4	7.16
6. Drive System	1465.5	1350.8	0.92	1455.1	1.00	1529.6	1.04
7. Fuel System	429.1	221.2	0.52	344.1	0.80	396.0	0.92
8. Propulsion Subsystem	143.0	297.2	2.0[illegible]	182.6	1.28	127.3	0.89
9. Flight Control Group	834.5	718.4	0.86	600.0	0.72	767.9	0.92
Σ (1...9)	7183.6	7105.3 7178.0	0.99 1.00	6994.7	0.97	7123.1	0.99

TABLE 2.12

WEIGHT SUMMARY
FOR 30,000 – 100,000 GROSS-WEIGHT PAIRS

ITEM	ACTUAL WEIGHT	METHOD					
		TISHCHENKO		BOEING VERTOL		RES. & TECH. LABS.	
	W_a ; lb	W_p ; lb	W_p/W_a	W_p ; lb	W_p/W_a	W_p ; lb	W_p/W_a
HELICOPTER	**Mi-6**						
1. Main-Rotor Blades	5953.5 7772.6	6416.8	1.08 0.83	6782.3	1.14 0.87	4965.0	0.83 0.64
2. Main-Rotor Hubs	7331.6	6314.4	0.86	3108.2 3419.5	0.42 0.47	8244.5	1.12
3. Tail-Rotor Group	1123.7 1274.5	904.3 1046.9	0.80 0.84	507.0	0.45 0.40	734.8 730.8	0.65 0.57
4. Fuselage	13,384.4	10,361.4	0.77	9812.3	0.73	13,043.2	0.97
5. Landing Gear	2802.6	1808.1	0.65	2712.2	0.97	1598.7	0.57
6. Drive System	8410.2 8472.0	7424.5	0.88	7555.0	0.90 0.89	8337.6	0.99
7. Fuel System	1180.8	1230.4	1.04	1503.8	1.27	4414.0	3.74
8. Propulsion Subsystem	1777.2	1289.9	0.72	1285.2	0.72	605.0	0.34
9. Flight Control Group	5479.4	3510.4	0.64	3600.8 3309.7	0.66 0.60	2117.6	0.39
Σ (1...9)	47,443.4 49,475.1	39,260.2 39,404.8	0.83 0.80	36,866.8 36,887.0	0.78 0.75	44,060.4 44,056.4	0.93 0.90
HELICOPTER	**CH-53E**						
1. Main-Rotor Blades	2884.9	3785.5	1.31	3044.8	1.06	2926.0	1.01
2. Main-Rotor Hubs	3472.1	3010.7	1.22	3471.0	1.00	2799.5	0.81
3. Tail-Rotor Group	584.4	948.1	1.62	432.3	0.74	533.1	0.91
4. Fuselage	8704.0	6720.2 7915.0	0.77 0.82	6977.2	0.80	8522.8	0.98
5. Landing Gear	1218.7	1120.0	0.92	1960.0	0.97	1598.7	0.57
6. Drive System	6257.1	6207.1	0.99	6062.6	0.97	6861.4	1.10
7. Fuel System	1225.0	595.0	0.60	926.1	0.94	1015.0	0.83
8. Propulsion Subsystem	630.3	1251.7	1.99	475.2	0.75	360.2	0.57
9. Flight Control Group	1658.1	2007.0	1.21	1765.1	1.06	1590.3	0.96
Σ (1...9)	26,634.6	25,645.3 26,840.1	0.96 1.01	25,114.3	0.94	26,207.0	0.98

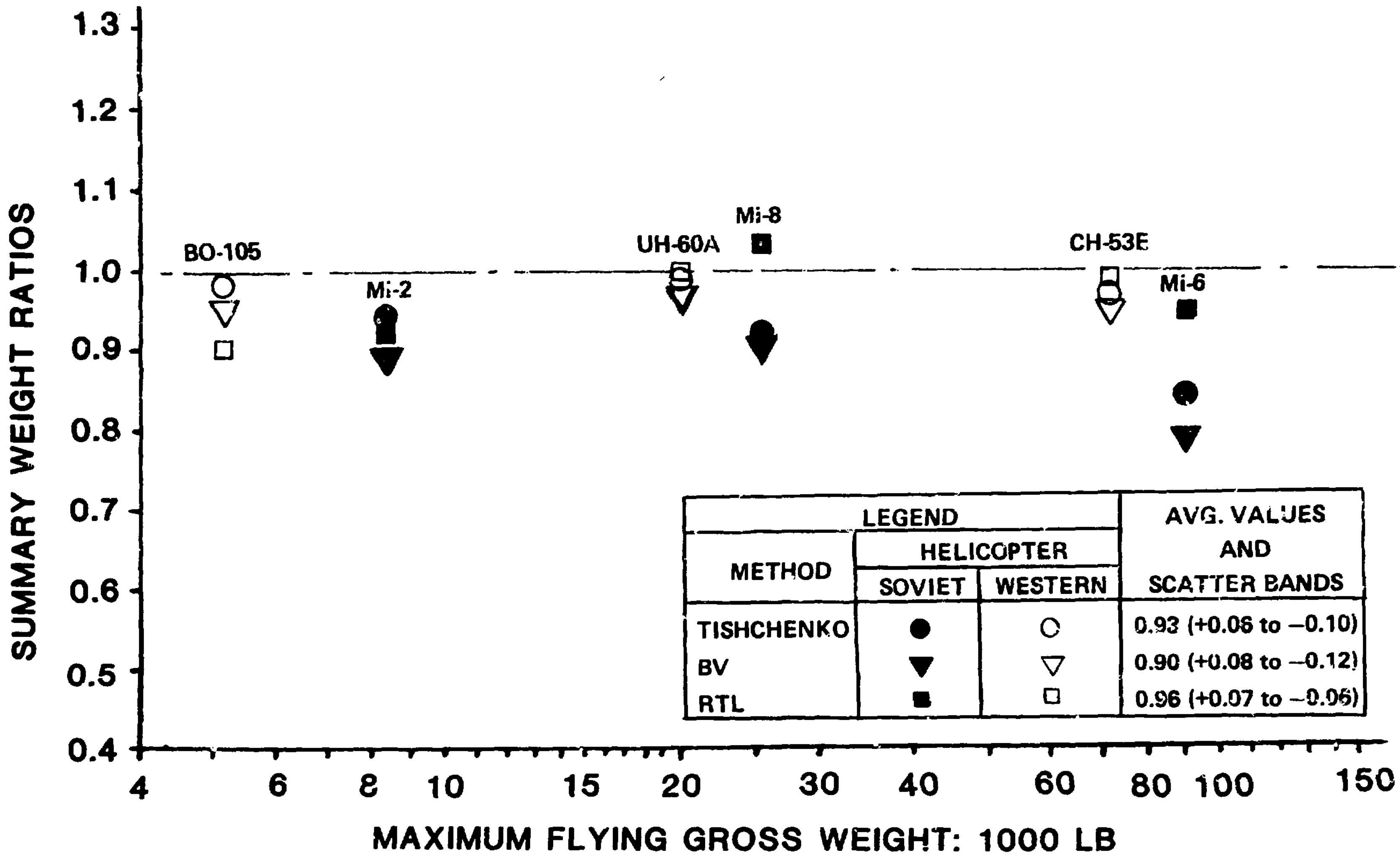


Figure 2.35 Summary weight of the nine major component ratios of predicted-to-actual weights

The use of Tishchenko's formula results in the corresponding predicted weight of 3069.0 lb, when k^*_{bl} = 13.8 is used, and increases to 3102.9 lb for the assumed value of k^*_{bl} = 15.2, while the related ratios of the predicted to actual summary weights are 0.93 and 0.94, respectively. This rather close prediction of the summary weight is somewhat surprising, since looking at the W_p/W_a ratio for the individual components, one would find considerable deviations from the ideal ratio value of 1.0.

The Boeing Vertol method leads to the summary weight of 2898.1, and the corresponding predicted-to-actual weight ratio of 0.88, which is worse than Tishchenko's; in spite of the fact that the weight ratios for the individual components are, in general, considerably better and with a lower width of the scatter band than the Soviet ones.

The RTL approach predicts a summary weight of 3045.8 lb, which results in the predicted-to-actual weight ratio of 0.92. This is a result close to that obtained by the Tishchenko method, although about 1 or 2 percent worse, again in spite of a much better consistency in predicting the weights of the individual components.

BO-105. A glance at the lower part of Table 2.10 would indicate that the actual major component summary weight amounts to 2030.0 lb.

The Tishchenko method would predict either 1985.9 or 2050.7 with corresponding weight ratios of 0.98 and 1.01. As in the case of the Mi-2, a very surprising result in view of the flagrant unrealistic weights of the individual major components.

The Boeing Vertol approach leads to predictions of 1918.5 and 1999.1 lb as summary weights, with corresponding ratios of 0.95 and 0.98. It should be noted that these results were obtained with much better estimates of the individual component weights than those of Tishchenko.

RTL weight equations lead to W_Σ = 1821.1 and 1856.1 lb, with the corresponding $W_{\Sigma_p}/W_{\Sigma_a}$ being equal to 0.90 and 0.91 which is worse than that of Tishchenko, although the consistency of the RTL method in predicting the weights of the individual major components is much better than that of Tishchenko.

Mi-8 – UH-60A Pair

Mi-8. It can be seen from the upper part of Table 2.11 that the lighter actual summary weight of major components (lighter main-rotor blades, and a lighter propulsion subsystem) amounts to 10,392.4 lb, while the heavier amounts to 10,861.1 lb.

Tishchenko-based computations would predict the lighter summary weight (corresponding to parameter values associated with the lighter weights) as 9367.6 lb and the heavier as 9563.3 lb, with corresponding ratios of $W_{\Sigma_p}/W_{\Sigma_a}$ = 0.91 and 0.88, respectively.

The Boeing-Vertol approach leads to very similar results, as the lighter weight predicted by this method amounts to 9374.5 lb and the heavier, 9448.2 lb; with corresponding ratios of $W_{\Sigma_p}/W_{\Sigma_a}$ = 0.90 and 0.87, respectively.

The RTL approach leads to the most accurate predictions of the summary weights of the major components, as it gives 10,940.0 lb for the heavier weight, and 10,695.1 for the lighter, with corresponding ratios of $W_{\Sigma_p}/W_{\Sigma_a}$ = 1.03 and 0.98, respectively.

UH-60A. Looking at the lower part of Table 2.11, one will find that the summary weight of the major components of the UH-60A amounts to 7183.6 lb.

Tishchenko-based computations predict that weight very closely by giving W_{Σ_p} = 7105.3 lb (for the lower predicted weight of the main-rotor blades, based on k^*_{bl} = 13.8) and W_{Σ_p} = 7178.0 lb when k^*_{bl} = 15.0 is used. The corresponding $W_{\Sigma_p}/W_{\Sigma_a}$ = 0.99 and 1.00, respectively – a surprising result, in view of the large errors in predictions of the individual component weights.

The Boeing-Vertol method also predicts the summary weight of the major components very closely, as W_{Σ_p} = 6999.7, leading to $W_{\Sigma_p}/W_{\Sigma_a}$ = 0.97. It should be emphasized however, that this result, although a shade worse than that of Tishchenko, stems from consistently very good to fair weight predictions of the individual major components.

The RTL approach consistently shows very good to good predictions of the individual weights of the major components, thus it comes as no surprise that the summary predicted weight of 7123.1 lb is very close to the actual weight, and that $W_{\Sigma_p}/W_{\Sigma_a}$ = 0.99.

Mi-6 – CH-53 Pair

Mi-6. The lower actual summary weight of the Mi-6 major components is 47,443.4 lb, and the higher weight is 49,475.1 lb (see the upper part of Table 2.12).

The Tishchenko method would predict the corresponding weights as 39,260.2 lb and 39,404.8 lb, with the corresponding ratios being $W_{\Sigma_p}/W_{\Sigma_a}$ = 0.83 and 0.8, respectively. Looking at the weight ratios of the individual major components, one would see that this time, those ratios are more consistent than in the previous case and, in general, all below 1.0. Consequently, the above summary of the weight ratios comes as no surprise.

The Boeing-Vertol method, similar to that of Tishchenko, predicts much lower summary weights than the actual ones; namely, 36,866.8 lb and 36,887.0 lb, with corresponding ratios of $W_{\Sigma_p}/W_{\Sigma_a}$ = 0.78 and 0.75, respectively. As in the preceding case, these results are considerably below the value of 1.0. Again, the results are of no surprise, since it can be seen from Table 2.12 that, in general, all except one of the predicted-to-actual weight ratios for the individual major components are well below 1.0.

The RTL approach is the only one that predicts summary weights close to the actual weights, as it gives 44,060.4 lb for the lighter, and 44,056.4 lb for the heavier weight, with corresponding ratios of $W_{\Sigma_p}/W_{\Sigma_a}$ = 0.93 and 0.89. However, the consistency of weight predictions by the RTL approach for the individual major components is much worse than for the Tishchenko and Boeing-Vertol methods.

CH-53E. The summary actual weight of the major components of the CH-53E is W_{Σ_a} = 26,634.6 lb (see the lower part of Table 2.12).

The Tishchenko approach again shows a close prediction of the actual weights (W_{Σ_a} = 25,645.3 for the lighter version and 26,840.1 for the heavier), with resulting ratios of $W_{\Sigma_p}/W_{\Sigma_a}$ = 0.96 and 1.01, respectively. As in the previously considered case of the Tishchenko approach, the result is surprising, since individual predictions of the major component weights are quite erratic.

The Boeing-Vertol method provides consistently good or very good weight predictions for the individual major components, so it is not surprising that the predicted weight of W_{Σ_p} = 25,114.3 lb results in a ratio of $W_{\Sigma_p}/W_{\Sigma_a} = 0.94$.

The RTL approach, although slightly less consistent in good predictions of the weights of the individual major components, predicts the summary weight very closely (W_{Σ_p} = 26,207 lb) with the corresponding ratio being $W_{\Sigma_p}/W_{\Sigma_a} = 0.98$.

2.12 Concluding Remarks

Structure of Weight Equations. The three methods of major component weight prediction considered in this chapter depend on statistical inputs representing existing helicopters. The modes in which the dependent parameters are expressed may follow many paths. For instance, a statistically justified value for a single weight coefficient corresponding to the design parameters appearing in the weight equation can be selected, wherein the design parameters would reflect as much as possible the physical considerations involved in the respective weight equation. Tishchenko's approach seems to follow the above-outlined path.

The Western approach as demonstrated by only two methods, RTL and Boeing Vertol, is somewhat different. Individual parameters and/or expressions consisting of several parameters contain originally undetermined coefficients and exponents of these terms. Values of these exponents and coefficients were selected in order to provide the best possible correlation with the statistical data.

Limits of Validity of Weight Equations. As a result of this dependence on statistical data, it may be expected that the major component weights of designs departing radically from the statistical data base may not be properly predicted. Because the weight equations are only as good as the data base from which the equations were derived, unique designs differentiating from the data base must be handled on an individual basis. This can be accomplished through adjustments to the existing weight equations to handle a given situation. It is important that the limitations be recognized and understood when applying the weight equations to concept formulations and preliminary designs.

A case in point may be represented by the Mi-6, where all three methods tend to under-predict most of the major component weights; thus indicating that the design itself is probably either over-conservative, or not on the weight efficiency level of contemporary helicopters. This hypothesis seems to be further confirmed by the fact that, indeed, the structural weight of its successor – the Mi-26 – has been substantially reduced. Unfortunately, there is no information available with respect to individual component weights to conduct a direct component-by-component comparison.

In light of this, Tishchenko's approach, because of its strong dependence on single-weight coefficients may be used with confidence when new design concepts closely resemble those on which the weight-coefficient values were based.

Boeing-Vertol and RTL methods, although also dependent on statistical trends, can be used in a much broader sense due to the multiple use of weight coefficients and exponents.

TABLE 2.13

SUMMARY OF INDIVIDUAL MAJOR COMPONENT WEIGHT PREDICTION TRENDS

MAJOR COMPONENT	AVERAGE RATIOS OF PREDICTED-TO-ACTUAL WEIGHTS					
	TYPE OF METHOD					
	TISHCHENKO		BOEING VERTOL		RTL	
Main Rotor Blades	0.98	+0.33 −0.41	1.00	+0.14 −0.11	0.96	+0.10 −0.13
Main Rotor Hubs and Hinges	1.25	+0.75 −0.39	0.78	+0.12 −0.31	1.00	+0.12 −0.19
Tail-Rotor Group	1.39	+0.69 −0.59	0.76	+0.30 −0.36	0.80	+0.15 −0.15
Fuselage	0.86	+0.12 −0.09	0.91	+0.15 −0.18	1.03	+0.22 −0.06
Landing Gear	0.70	+0.22 −0.27	1.07	+0.53 −0.43	0.95	+0.26 −0.38
Drive System	0.87	+0.12 −0.19	0.92	+0.07 −0.11	0.92	+0.18 −0.21
Fuel System	0.92	+0.43 −0.40	1.02	+0.25 −0.20	1.44	+2.30* −0.61
Propulsion Subsystem	1.22	+0.85 −0.81	0.96	+0.32 −0.29	0.89	+0.98 −0.55
Flight Control Group	0.85	+0.36 −0.21	0.84	+0.22 −0.18	0.75	+0.21 −0.36
Flight Control Group (Excluding the Mi-6)	0.89	+0.32 −0.20	0.88	+0.18 −0.16	0.82	+0.14 −0.18

*With Mi-6 excluded: 0.98 (+0.31 to −0.15)

<u>Accuracy of Weight Prediction of Individual Major Components.</u> With respect to the weight predictions of individual major components; in some cases, Boeing Vertol while in others, RTL methods appear to provide more accurate predictions than Tishchenko's approach. This can be seen from Table 2.13 which summarizes the average values and scatter bands previously individually shown in Figs. 2.4, 2.7, 2,11, 2.14, 2.16, 2.17, 2.24, 2.25, 2.28, and 2.34.

Main-Rotor Blades. It can be seen from Table 2.13 that the mean values are very good for all three methods. However, the scatter band for Tishchenko is +0.33 to −0.41, thus showing that very large individual errors may occur using their approach. By contrast, the Boeing-Vertol and RTL approaches show much narrower scatter bands; hence, resulting in a higher confidence in the weights predicted by these approaches.

Main-Rotor Hub. The Tishchenko method of predicting average main-rotor hub weights appears to be poor, and even worse results are obtained regarding the consistency of the predictions. Boeing Vertol shows a strong tendency toward underprediction, plus a relatively large margin of error. However, when the Mi-6 is excluded, both the average and the scatter band improve: average, 0.86 (scatter band, from +0.14 to −0.22). The RTL method seems to be very good in regard to both the average value and the scatter band.

Tail-Rotor Group. None of the three methods appear very good. However, the RTL approach seems to be best regarding both the average value and the scatter band.

Fuselage. All three methods give acceptable results; the Western approach being somewhat superior to that of Tishchenko. The RTL method may have some edge over that of Boeing Vertol.

Landing Gear. Using the recommended weight coefficient value, the Tishchenko formula greatly underpredicts the landing-gear weights, but the scatter band, although wide, is somewhat narrower than that of Boeing Vertol and RTL. The RTL formula appears to give better results than that of Boeing Vertol.

Drive System. All of the three considered methods lead to acceptable weight predictions. However, the Western approaches seem to be somewhat superior to that of Tishchenko. In addition, the Boeing-Vertol equations appear to be slightly better than those of RTL because of a narrower scatter band.

Fuel System. Of the three compared methods, the Boeing-Vertol approach appears to give the most correct weight predictions on the average, but the scatter band is quite wide. When the Mi-6, with its large number of fuel tanks is excluded, the RTL equations give very good average fuel system weight predictions, but the scatter band is still quite wide. Tishchenko's approach leads to good average values, but the scatter band is wider than for either the Boeing-Vertol or RTL (with the Mi-6 excluded) methods.

Propulsion Subsystem. In this case, none of the three compared methods is very good in predicting the propulsion subsystem component weights. However, the Tishchenko approach appears as the least reliable, because of both the average values and width of the scatter band. The RTL approach is not much better. The Boeing-Vertol equations, because of their good average score and narrower scatter band, seem to provide the most accurate, but still not completely satisfactory, weight predictions.

Flight Control Group. When the Mi-6 is included, all three methods on the average, show a tendency to greatly underpredict the component weights of the flight control group. However, with the

exclusion of the Mi-6, the situation is somewhat improved, but still all three methods retain their tendencies toward underprediction. While the scatter bands for the Western approaches are not excessively wide, they are much wider for the Tishchenko equations. Within this not too satisfactory overall picture, the Boeing Vertol method appears to give the best results of the three.

Summary

- When reading this report one must realize that the whole study is of limited character, since out of many existing methods, only three (one Soviet and two Western) were selected for comparison. Furthermore, the number of compared aircraft was also limited, consisting of three pairs only.

- Weight prediction equations in the West and probably also in the Soviet Union are in a state of flux, as they are constantly being refined, updated, and sensitized.

- Probably all of the weight equations in present use are based on statistical data of already built helicopters. Consequently, they are only as good as the data on which they are based.

- Unique situations wherein deviations from the general trend may be expected must be handled on an individual basis.

- In actual preliminary design practice, a lot of a' priori judgement must be used. This is usually done in such a way that 'destined for use' equations are adjusted to reflect the current state of the art, variation in size, and use of any of the technologies above and beyond the baseline technology base.

- No one set of the compared weight equations proved to be superior. Rather, each set offered a unique observence of trends within the limited data comparison. This comparison showed the possible pluses and minuses of each weight equation.

- At this time, weight equation derivation is a statistical game, and the proper use of the derived expressions requires proper engineering judgement and prudent application.

APPENDIX TO CHAPTER 2

ACTUAL WEIGHTS OF MAJOR SOVIET HELICOPTER COMPONENTS

Most of the actual weights of major components for the three Soviet helicopters considered in this chapter are directly given in various tables of Ref. 1. However, this type of information is missing for the following items: boosted main-rotor controls, swashplate assembly, manual (pre-boost) controls, engine installation, and landing gear. Fortunately, graphs showing weight coefficient values of these items as well as formulae relating those coefficients to the compared weights are given in the reference. Using these graphs and formulae (rewritten here in the present notations), the actual weights of the components were computed as shown in Tables A-1 through A-8.

As a matter of general information, it should be noted that the actual weight of the total engine system and equipment are also calculated, although these items are not included in the comparison performed in Chapter 2. Then the actual weights of the three Soviet helicopters are summarized in Table A-9, along with the specified empty weights.

DETERMINATION OF COMPONENT WEIGHTS OF SOVIET HELICOPTER FROM GRAPHS IN REF. 1

Boosted Main-Rotor Controls (Fig. 2.10[1])

$$W_{bc} = (n_{bl} c^2 R) \times k_{bc}$$

ITEM		HELICOPTER		
		Mi-2	Mi-8	Mi-6
n_{bl}		3	5	5
c: m		0.400	0.520	1.00
R: m		7.25	10.65	17.50
k_{bc}: kg/m^3		22.0	19.0	17.0
W_{bc}	kg	76.52	273.6	1487.5
	lb	168.8	603.3	3279.9

TABLE A-1

Swashplate Assembly (Fig. 2.10[1])

$$W_{sp} = (n_{bl} c^2 R) \times k_{sp}$$

ITEM		HELICOPTER		
		Mi-2	Mi-8	Mi-6
n_{bl}		3	5	5
c: m		0.400	0.520	1.00
R: m		7.25	10.65	17.50
k_{sp} : kg/m^3		8.00	8.00	8.00
W_{sp}	kg	27.84	115.19	700
	lb	61.39	253.99	1543.5

TABLE A-2

Manual (Pre-boost) Controls (Fig. 2.11[1])

$$W_{mc} = k_{mc} \times R_{mr}$$

ITEM		HELICOPTER Mi-2	Mi-8	Mi-6
R: m		7.25	10.65	17.50
k_{mc}		7.0	9.0	17.0*
W_{mc}	kg	50.75	95.85	297.5
	lb	119.90	211.35	655.99

TABLE A-3

*Manual & auxiliary controls, together with auxiliary hydraulic system

Engine Installation (Fig. 2.31[1])

(weight of propulsion subsystems)

$$W_{pss} = \Sigma SHP_{ref} \times k_{pss}$$

ITEM		HELICOPTER Mi-2	Mi-8	Mi-6
ΣSHP_{ref}: hp		800	3000 4000	13,000
k_{pss}		0.1125	0.045 0.052	0.062
W_{pss}	kg	90.0	135.0 208.0	806
	lb	198.45	297.67 458.64	1777.23

TABLE A-4

Total Engine System

$$W_{e.s} = \Sigma W_{eng} + W_{pss}$$

ITEM	HELICOPTER Mi-2	Mi-8	Mi-6
ΣW_{eng}: lb	596.00	1454.00	5842.00
W_{pss}: lb	198.45	297.67 458.64	1777.23
$\Sigma W_{eng} + W_{pss}$: lb	794.45	1751.67 1912.54	7619.23

TABLE A-5

Fuel System (Fig. 2.32[1])

$$W_{fs} = (W_{fu})_{tot} \times k_{fs}$$

ITEM		HELICOPTER Mi-2	Mi-8	Mi-6
$(W_{fu})_{tot}$: kg		500	1450	6300
k_{fs}		0.072	0.113	0.085
W_{fs}	kg	36.0	163.85	535.5
	lb	79.38	361.29	1180.78

TABLE A-6

Landing Gear (Fig. 2.42[1])

$$W_{lg} = k_{lg} \times (W_{gr})_{des}/100$$

ITEM		HELICOPTER Mi-2	Mi-8	Mi-6
$(W_{gr})_{des}$: kg		3700	11,100	41,000
$k_{lg}/100$		0.028	0.028	0.031
W_{lg}	kg	103.60	310.8	1271.0
	lb	228.44	685.3	2802.56

TABLE A-7

Equipment (Without Electric Installation) (Fig. 2.43[1])

$$W_{eqp_o} = k_{eqp} W_{gr}^{0.6}$$

ITEM		HELICOPTER Mi-2	Mi-8	Mi-6
W_{gr}: kg		3700	11,100	41,000
$(k_{eqp})_{av}$		2.05	2.2	2.1
W_{eqp_o}	kg	283.58	588.32	1229.96
	lb	625.29	1297.25	2712.05

TABLE A-8

TABLE A-9

ACTUAL MAJOR COMPONENT WEIGHTS OF SOVIET HELICOPTERS

COMPONENT		ACTUAL MAJOR COMPONENT WEIGHTS: W_{comp}					
		HELICOPTER					
		Mi-2		Mi-8		Mi-6	
		kg	lb	kg	lb	kg	lb
1. Main-Rotor Blades		165.0	363.8	679.0[a]	1477.4[a]	3200.0[b]	7056.0[b]
2. Main-Rotor Hub(s)		132.0	291.1	605.0	1334.0	3325.0	7331.6
3. Controls (Swashplate Assembly)		27.8	61.4	115.2	254.0	700.0	1543.5
4. Boosted Controls W/Hydraulic System		76.5	168.8	273.6	603.3	1487.5	3279.9
5. Manual Controls		50.7	119.9	95.8	211.3	297.5	656.0
6. Main Gearboxes (W/Lubricating System)		284.0	626.2	782.0	1724.3	3200.0	7056.0
7. Intermediate Gearboxes		14.0	30.9	22.0	48.5	114.0	251.7
8. Tail-Rotor Gearbox		18.0	39.7	48.0	105.8	286.0 297.0[c]	630.6 654.9[c]
9. Tail-Rotor Blades		7.2	15.9	41.4[d]	90.6	256.0[e] 109.6[f]	564.5[e] 241.7[f]
10. Tail-Rotor Hubs		17.0	37.5	76.5	168.7	322.0[e] 400.0[f]	710.0[e] 882.0[f]
11. Transmission Shafts		24.2	53.4	49.3	108.7	214.0 231.0[c]	471.9 509.4[c]
12. Engine Installation (Total)		360.3	794.4	794.4 867.4	1751.7 1912.6	3455.4	7619.2
13. Fuel System		36.0	79.9	163.8	361.3	535.5	1180.8
14. Fuselage w/Cowlings & Engine Controls		445.0	981.2	1465.0	3230.3	6070.0	13384.4
15. Landing Gear		103.6	228.4	310.8	685.3	1271.0	2802.6
16. Equipment		283.6	625.3	588.3	1297.3	1230.0	2712.1
WEIGHT EMPTY	ΣW_{comp}	2044.9	4517.8	6110.1 6183.1	13,452.5 13,613.4	25,963.9 25,923.5	57,250.8 57,161.8
	SPECIFIED	2375.0[i] 2505.0[j]	5836.9 5523.5	6816.9[g] 7261.0[h]	15026.0 16007.0	27236.0[i]	60,055.0

NOTES:

[a] blades w/Duraluminum extruded spar

[b] mid[illegible] value from Table 2.1[1]

[c] for 6500 hp/engine

[d] production blades, Table 2.4[1]

[e] wooden production blades

[f] constant-chord metal blades (Variant II), Table 2.4[1]

[g] cargo version

[h] passenger version

[i] Jane's

[j] PZL brochure

Chapter 3
Component Design Comparison

3.1 Introduction

Objectives. In principle it would be interesting to compare the major components of Soviet and Western helicopters by examining in parallel, and in some detail, the basic design philosophies of those components and then, if possible, quantitatively evaluate the success of the two approaches in meeting the various criteria of a successful design. However, because of the lack of necessary information regarding the design details of Soviet helicopters and the limited scope of this study, a detailed discussion of the design philosophy of major components will be omitted, focusing our attention on a few of the design aspects which may serve as a criteria of the success of the design. This will be done by looking at such major component characteristics as (a) relative weight, (b) maintainability, and (c) overall merits of the design.

Relative Weight. The relative weights expressed as ratios of major component weights with respect to either design or maximum flying gross weights may serve as a criterion regarding the success of design in the important area of lightweight airframe structure. In order to provide a broader perspective in this area, information regarding some additional Western helicopters considered in Part 1 will also be incorporated. Furthermore, the weights of the major components of the so-called 'hypothetical' Soviet helicopters given in Ref. 1 will also be included, as these helicopters appear to reflect the trend of their current and future design philosophy. To gain some additional insight into these trend aspects, a comparison will be made of the major component weight averages representing various configurations of Western and Soviet traditional as well as hypothetical helicopters (e.g., single-rotor, tandems, and side-by-side).

Maintainability. The subject of maintainability is discussed by Sloan, wherein he points out that information regarding overhaul tours and other service data on Soviet helicopters is very limited, as it is restricted to the Mi-2 only. However, on the basis of this limited information which is considered typical for traditional Soviet helicopter designs, and some inputs from other sources, a generalized comparison between Soviet and Western approaches to maintainability is given.

Overall Merits of Component Design. The overall merits of component design are discussed by Tarczynski wherein he points out that in the proposed approach, an attempt is made to develop a numerical index of merit that would permit one to quantitatively rate the components of a given type as represented by various Soviet and Western helicopters. In order to perform this rating, special index-of-merit tables are worked out a'priori, and then points are awarded for various design features considered as meritorious. Since the proposed approach is new and may generate some controversy regarding the importance of a specific design aspect and thus the number of points it deserves, only two major components are comparatively evaluated; namely, main-rotor blades and hubs.

Rating of Helicopter Configurations for Transport Applications. In Ref. 1, various transport helicopter configurations of the 15 to 60 m.ton gross-weight range were rated regarding maximization of absolute (W_{pl}) and relative (W_{pl}/W_{gr}) payloads for short (50 km) and long (800 km) flight distances. The validity of Tishchenko's rating – single-rotor first, then side-by-side, and finally, tandem – could be ascertained through a complete process of sizing (similar to Ref. 2); however, an approximate, but probably correct answer as far as the sequence of rating is concerned, was obtained through a determination of differences in the relative payload by using the relative weights established at the beginning of Ch. 3. This task is performed in the Appendix to this chapter.

3.2 Relative Weights of Major Components

General. The nine major helicopter components (main-rotor blades, main-rotor hubs, tail-rotor group, fuselage, landing gear, drive system, fuel system, propulsion subsystem, and flight control group) of the six helicopters considered in Ch. 2 were selected for relative-weight comparisons. Here, relative weights based on design and maximum flying gross weights were computed and then presented in the form of tables and graphs.

However, in order to widen the data bases, especially with respect to Western tandem configurations, inputs on the CH-47D and XCH-62A were also included and, to complete the picture regarding current and future trends in Soviet rotary-wing design philosophy, data on the following hypothetical helicopters were also incorporated: (1) single rotor (15 and 52 m.ton design gross weights), (2) side-by-side (52 m.ton design gross weight), and (3) tandem (15 and 52 m.ton gross weights).

It should be noted at this point that in Tables 3.2 through 3.10, and Figs. 3.1 through 3.9, clearly recognizable symbols are used to define rotor configurations (single horizontal bar for single-rotor, two horizontal bars on the same level for the side-by-side, and horizontal overlapping bars for the tandem); and gross-weight type (dots for designs or normal gross weights, and inverted triangles for the maximum flying gross weights). Furthermore, Western rotary-wing aircraft are designated by open symbols, Soviet existing aircraft are designated by closed symbols, and Soviet hypothetical machines by partially closed symbols.

With respect to data regarding component weights of Soviet hypothetical helicopters, it should be noted that the weights of the major components of the 15 m.ton machines are explicitly listed in Table 2.8[1] and consequently shown in Table 3.1 of this report. The component weights for the 52 m.ton class are presented in graphical form in Ref. 1 as functions of rotor diameters for a fixed number of blades. Using the rotor diameters and number of main-rotor blades for the single-rotor and side-by-side configurations determined in Part 1 of this report, it was possible to establish the appropriate major component weights from Figs. 2.79 and 2.85 of Ref. 1. These weights are also listed in Table 3.1.

Additional information (e.g., maximum flying gross weight and power installed) is also contained in Part 1 of this report for the 15 and 52 m.ton single-rotor, and 52 m.ton side-by-side hypothetical

TABLE 3.1

MAJOR COMPONENT WEIGHTS OF SOVIET HYPOTHETICAL HELICOPTERS

MAJOR COMPONENT WEIGHT IN (KG) AND LB					
MAJOR COMPONENT	SOVIET HYPOTHETICAL HELICOPTER				
	SR 15 m.ton[a]	T 15 m.ton[a]	SR 52 m.ton[b]	SBS 52 m.ton[c]	T 52 m.ton[d]
Main-Rotor Blades	(616) 1358.3	(768) 1693.4	(3300) 7276.5	(2100) 4630.5	(3470) 7651.4
Main-Rotor Hubs & Hinges	(538) 1186.3	(846) 1865.4	(3150) 6945.8	(2100) 4630.5	(3150) 6945.8
Tail-Rotor Group	(157) 346.2		(750) 1653.8		
Fuselage	(1916) 4224.8	(2181) 4809.1	(5255) 11,587.3	(7850)[e] 17,309.3[e]	(7250) 15,986.8
Landing Gear	(450) 992.3	(450) 992.3	(1080) 2381.4	(1550) 3417.8	(1315) 2899.6
Drive System	(1235) 2723.2	(1434) 3162.0	(4870) 10,738.4	(5080) 11,201.4	(6580) 14,508.9
Fuel System	(130) 286.7	(135) 297.7	(780) 1719.9	(800) 1764.0	(844) 1861.0
Propulsion Subsystem					
Flight-Control Group	(609) 1342.8	(759) 1675.6	(1650) 3638.3	(1500) 3307.5	(2050) 4520.3
Vibration Absorbers		(375) 826.9			(850) 1874.3

NOTES:
(a) Table 2.8[1]
(b) Fig. 2.79[1]
(c) Fig. 2.85[1]
(d) Fig. 2.82[1]
(e) Including outriggers

helicopters. However, since no such information was available for the 52 m.ton gross weight hypothetical tandem, the following deductions were made to fill the gap.

It was indicated in Fig. 2.. 3[1] that for the hypothetical tandem with 5-bladed rotors, maximum payloads of approximately 9 m.ton at 800 km, and over 17 m.ton at 50 km ranges were realized. Now, looking at Figs. 2.80 and 2.81 of Ref. 1, one would realize that these maximum payloads were achieved for the 5-bladed rotor, where the rotor diameter was approximately $D = 30.3$ m ($R = 49.77$ ft). Consequently, all component weights shown in Table 3.1 for the 52-ton tandem were read from Fig. 2.62[1], assuming $D = 30.3$. It should be noted at this point that although Figs. 2.80, 2.81, and 2.86 of Ref. 1 indicate that the 5-bladed rotor configuration is optimal, blade and presumably hub weights are shown in Fig. 2.82[1] for 4-bladed rotors only. Thus, of necessity, blade weights corresponding to $n = 4$ are shown in Table 3.1.

In order to compute the maximum flying gross weight, which was presumed to be an OGE hovering weight at SL standard, the available takeoff SHP must be determined. It can be seen from Fig. 2.82[1] that for $D = 30.3$ m, the referred power $N'' = 21{,}875$ hp. Assuming a lapse rate of 0.96 and remembering that $c_{hp} \equiv 0.9863$ hp, the takeoff power at SL would be $SHP_{TO} \approx 22{,}500$ hp. Using this figure, and assuming that $FM_{oa} \equiv 0.6$, the SL hovering weight OGE is computed from Eq. (6.2), Part 1, as $W_{gr_h} = 159{,}940$ lb. This value is so high that the maximum flying weight is arbitrarily limited to $W_{gr_{max}} = 114{,}660 \times 1.25 = 143{,}325$ lb, and this figure will be used as the maximum permissible flying weight.

Main-Rotor Blades. The weights of the main-rotor blades, as well as their percentile contribution to the design and maximum flying weights are listed in Table 3.2. The relative weights are also graphically shown in Fig. 3.1.

Fig. 3.1 and Table 3.2 both show that the average relative blade weight for all the considered helicopters is approximately 5.63 percent when based on design gross weight, and 4.91 percent when referred to the maximum flying gross weight. However, considerable deviations from the average are encountered in various helicopters (e.g., 8.70 and 8.29 percent respectively, for the heavier blades of the Mi-6).

With respect to the Mi-2, one of the three Soviet "traditional-design" helicopters examined, the relative blade weights are below the average, and even slightly lower than those of their Western counterparts.

The relative weight of the lighter set of the Mi-8 blades, when referred to the design gross weight, is close to the average value, and not much different from that of its Western counterparts. However, when the maximum flying gross weight is used as a reference, the relative weight is somewhat higher than that of the West.

In contrast to comparable Western helicopters, the relative blade weight for the Mi-6 is higher than average for the lighter set of blades and considerably higher for the heavier set.

It is interesting to note that the relative blade weights given for both the 15 m.ton single-rotor and the 52 m.ton side-by-side hypothetical machines project considerably lower than average values.

TABLE 3.2

EXPLICIT & RELATIVE MAIN-ROTOR BLADE WEIGHTS

HELICOPTER	WEIGHTS				
	DESIGN GW LB	MAX. FLYING GW; LB	BLADES LB	RELATIVE % BASED ON:	
				DESIGN GW	MAX.FLYING GW
WESTERN					
BO-105	4442	5114	268	6.03	5.24
YUH-61A	15,157	19,700	872.2	5.78 "	4.43 "
UH-60A	16,260	20,250	841.0	5.17 "	4.15 "
CH-53E	56,000	73,500	2884.9	5.15 "	3.92 "
CH-47D	42,700	50,000	2130.0	4.99	4.26
XCH-62A	118,000	148,000	6264.3	5.31 "	4.23 "
SOVIET ACTUAL					
Mi-2	7826	8175	364.0	4.65	4.45
Mi-8	24,470	26,455	1278/1477	5.22/6.04 "	4.83/5.58 "
Mi-6	89,285	93,700	5951/7769	6.67/8.70 "	6.35/8.29 "
SOVIET HYPO					
SR 15 m.ton	33,075	[38,760]	1358.3	4.11	3.50
Tand. 15 m.ton	33,075		1693.4	5.12	
SR 52 m.ton	114,660	[131,375]	[7276.5]	6.35	5.55
SBS 52 m.ton	114,660	[129,210]	[4630.5]	4.04	3.58
Tand. 52 m.ton	114,660	[143,325]	[7651.4]	[illegible]	5.34
AVERAGE VALUES				5.63	4.91

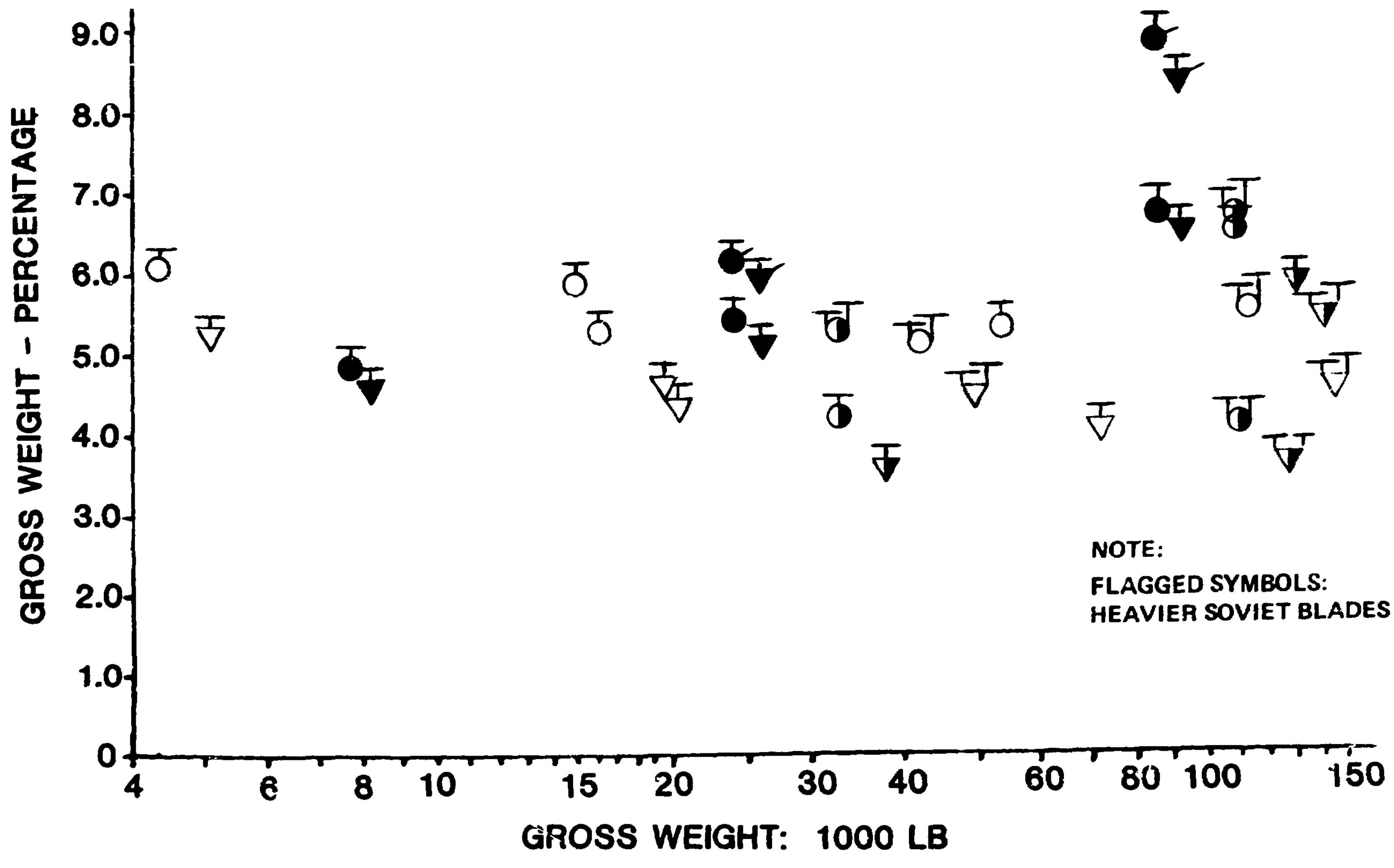


Figure 3.1 Relative weights of main-rotor blades

However, higher than average relative blade weights (only slightly lower than the Mi-6 lighter figure) are foreseen for the 52 m.ton single-rotor machine, which is still considerably higher than that for such Western counterparts as the CH-53E and XCH-62A. The blade weights of the hypothetical 15 m.ton tandem are anticipated to be about 25 percent heavier than those of the corresponding single-rotor machine, and also somewhat higher (by about 5 percent) for the 52 m.ton tandem helicopter. The relative blade weights of the hypothetical 15 m.ton tandem (referred to design gross weight) are almost the same as for the CH-47D, while for the 52 m.ton machine, the relative blade weights are about 26 percent higher than for the XCH-62A.

Main-Rotor Hubs and Hinges. Explicit and relative weights of main-rotor hubs and hinges are listed in Table 3.3, and the relative values are graphically presented in Fig. 3.2. Both the table and figure indicate that the average relative weight of the main-rotor hubs and hinges amounts to 5.03 percent when referred to design, and 4.26 percent when related to maximum flying gross weights. However, as in the preceding case of blades, considerable deviations from the average can be encountered. Furthermore, looking at Fig. 3.2, one would note that there is a general trend for an increase in the relative hub and hinge values with increasing gross weight.

It can be seen from Fig. 3.2 that for the three Soviet helicopters of "traditional" design considered in this study, the relative hub and hinge weights of the Mi-2 is on the same level as its Western counterparts, while for the Mi-8, is considerably higher than for Western helicopters of the same class (e.g., by 68 percent higher than for the UH-60A when related to maximum flying gross weight). As in the case of some of the other major components, the Mi-6 is the "heavy" champion as far as the relative weight of its rotor and hinges are concerned (8.21 percent based on design, and 7.82 percent referred to maximum flying gross weights).

Lower than average relative hub and hinge weight values are foreseen for the 15 m.ton gross weight single-rotor and 52 m.ton side-by-side Soviet hypothetical helicopters, while that ratio for the single-rotor 52 m.ton hypothetical machine, although much lower than for the Mi-6, is still anticipated to be about 20 percent higher than the average when related to the design gross weight. With respect to the hypothetical 15 m.ton tandem, the ratio is much higher than for the single-rotor configurations of the same design gross weight; and is forecast to be almost twice that of the CH-47D. By contrast, the relative hub and hinge weights (based on design gross weight) for the 52 m.ton tandem are identical to those of the corresponding single-rotor machine, and very similar to those of the XCH-62A.

Tail-Rotor Group. Explicit and relative numerical weight data are given in Table 3.4, and the relative values are graphically shown in Fig. 3.3 It can be seen from Table 3.4 that the average relative weights of the tail-rotor group amount to 0.95 percent when based on design gross weights, and 0.84 percent when related to maximum flying gross weights.

As in the two previously discussed cases, individual values considerably deviate from the averages. Furthermore, it should be noted from Fig. 3.3 that a definite general trend exists for an increase in the relative tail-rotor group weights along with increasing gross weights of the helicopters. It also may be

TABLE 3.3

EXPLICIT & RELATIVE MAIN–ROTOR HUB & HINGE WEIGHTS

HELICOPTER	WEIGHTS				
	DESIGN GW LB	MAX. FLYING LB	MAIN-ROTOR HUBS & HINGES LB	RELATIVE % BASED ON: DESIGN GW	RELATIVE % BASED ON: MAX.FLYING GW
WESTERN					
BO-105	4442	5114	200.5	4.51	3.92
YUH-61A	15,157	19,700	518.5	3.42	2.63
UH-60A	16,260	20,250	605.9	3.73	2.99
CH-53E	56,000	73,500	3472.1	6.20	4.72
CH-47D	42,700	50,000	1524.0	3.57	3.05
XCH-62A	118,000	148,000	7306.4	6.19	4.94
SOVIET ACTUAL					
Mi-2	7826	8175	291.1	3.72	3.56
Mi-8	24,470	26,455	1333.0	5.45	5.03
Mi-6	89,285	93,700	7331.6	8.21	7.82
SOVIET HYPO					
SR 15 m.ton	33,075	[38,760]	1186.3	3.59	[3.06]
Tand. 15 m.ton	33,075		1365.4	5.64	
SR 52 m.ton	114,660	[131,375]	6945.8	6.06	[5.29]
SBS 52 m.ton	114,660	[129,210]	4630.5	4.04	[3.58]
Tand. 52 m.ton	114,660	[143,325]	6945.8	6.06	[4.85]
AVERAGE VALUES				5.03	4.26

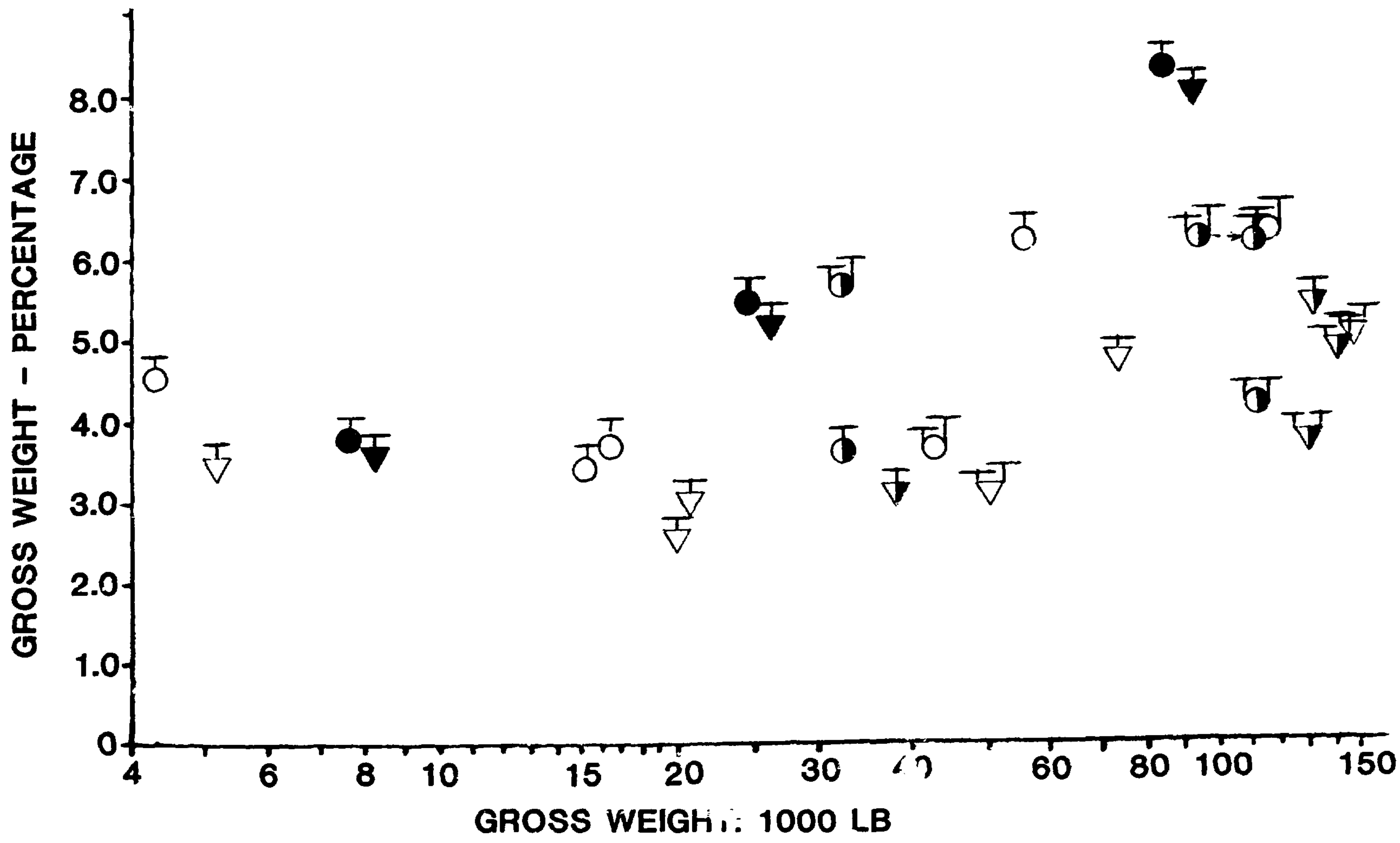


Figure 3.2 Relative weights of main-rotor hubs and hinges

TABLE 3.4

EXPLICIT & RELATIVE TAIL-ROTOR GROUP WEIGHTS

HELICOPTER	WEIGHTS				
	DESIGN GW LB	MAX. FLYING LB	TAIL–ROTOR GROUP; LB	RELATIVE % BASED ON: DESIGN GW	RELATIVE % BASED ON: MAX.FLYING GW
WESTERN					
BO-105	4442	5114	21.9	0.49	0.43
YUH-61A	15,157	19,700	82.1	0.54 "	0.42 "
UH-60A	16,260	20,250	122.9	0.76 "	0.61 "
CH-53E	56,000	73,500	584.4	1.04 "	0.80 "
CH-47D	42,700	50,000			
XCH-62A	118,000	148,000		"	"
SOVIET ACTUAL					
Mi-2	7826	8175	53.4	0.66	0.65
Mi-8	24,470	26,455	150/259	0.61/1.06 "	0.57/0.98 "
Mi-6	89,285	93,700	1124/1274.5	1.26/1.43 "	1.20/1.36 "
SOVIET HYPO					
SR 15 m.ton	33,075	[38,760]	364.2	1.10	0.94
Tand. 15 m.ton	33,075				
SR 52 m.ton	114,660	[131,375]	1653.8	1.44	1.26
SBS 52 m.ton	114,660	[129,210]			
Tand. 52 m.ton	114,660	[143,325]			
AVERAGE VALUES				0.95	0.84

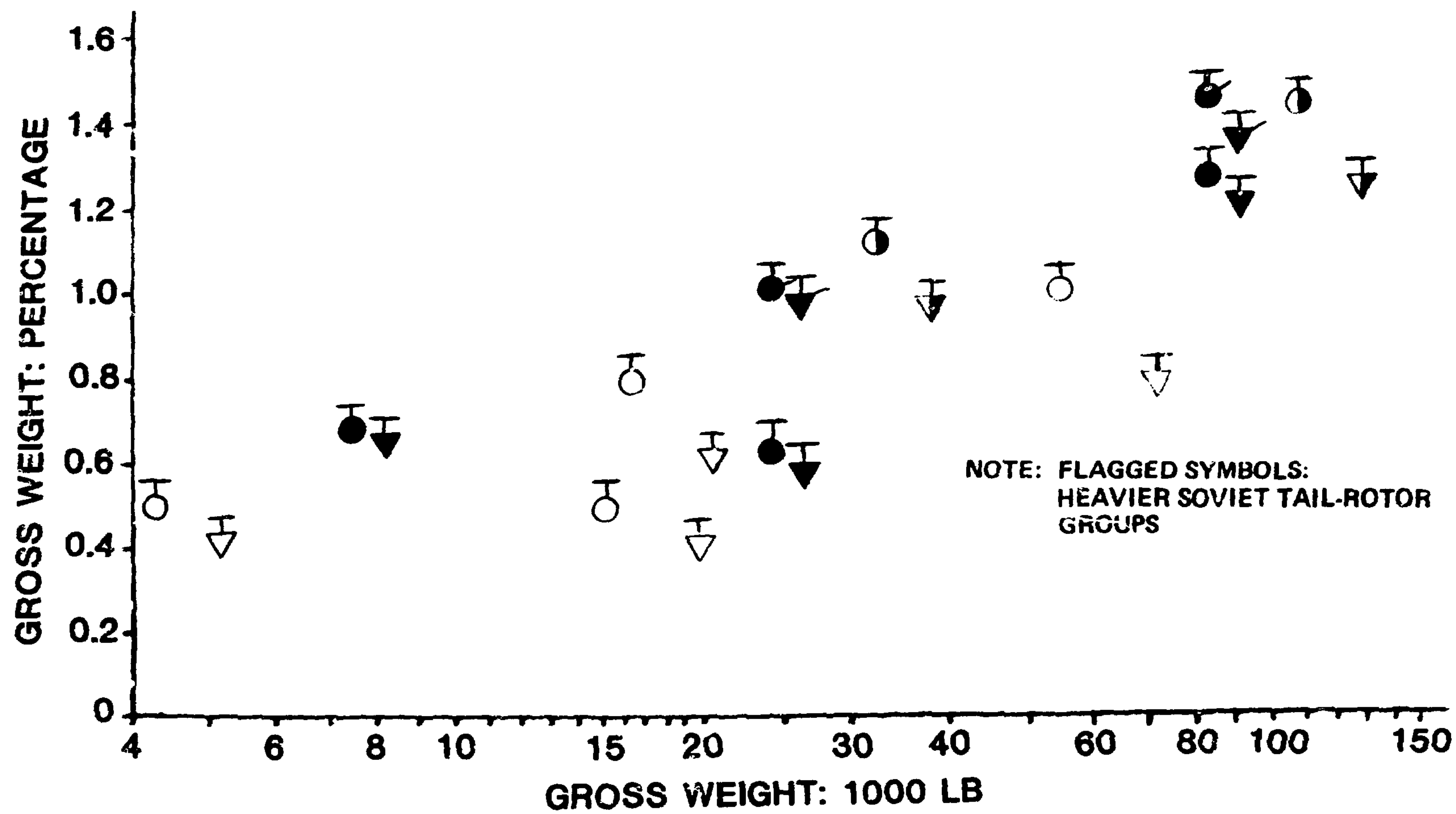


Figure 3.3 Relative weights of tail rotor group

noted from this figure that with the exception of the lighter tail-rotor group for the Mi-8, all Soviet traditional designs and those projected for hypothetical machines seem to show more of a trend toward higher relative weights of the tail-rotor group than their Western counterparts. Also of interest may be the fact that contrary to other major components, practically no improvement in relative weight trends for the tail-rotor group is foreseen in the hypothetical designs.

Fuselage. Explicit and relative weights of fuselages (body group) are listed in Table 3.5, and the relative values are graphically shown in Fig. 3.4. Upon examining this table, one will find that for all the helicopters considered here, the average value of the relative body-group weight amounts to 12.86 percent when based on design, and 11.02 percent when referred to maximum flying weights.

It can be determined from both Table 3.5 and Fig. 3.4 that considerable deviations from the average values may be encountered. For instance, it appears that the lowest ralative fuselage weight is demonstrated by the XCH-62A (7.91 percent based on design, and 6.31 percent when related to maximum flying weight). The CH-47D tandem also shows a below average fuselage weight. By contrast, the heaviest relative fuselage weight is found in the CH-53E – 15.54 percent when referred to design gross weight. However, when the reference base is changed to maximum flying gross weight, that figure drops down to 11.84 percent, which is not much different from the average for all the considered helicopters.

The Mi-6 has the highest relative body group weight with respect to maximum flying gross weight (14.28 percent). It appears, hence, that the existing Soviet heavy-lift single-rotor helicopters exhibit relative fuselage weights above the average. But, in Ref. 1, it was assumed that the hypothetical 15 m.ton single-rotor helicopters would have close to average relative fuselage weights (12.77 percent based on design and 10.9 percent based on maximum flying gross weights). In contrast, 14.4 and 13.94 percent respectively, were assumed at design gross weights for the 15 and 52 m.ton hypothetical tandems.

High relative fuselage weight values (15.1 percent for design and 13.4 percent for maximum flying weight) are indicated for the 52 m.ton side-by-side configuration. However, this is of no surprise, since outriggers and main gearbox attachments are assumed to belong to the body group.

Landing Gear. One can see from Table 3.6 and Fig. 3.5 that the landing-gear relative weights of both Soviet and Western helicopters are, in general, close to the average of 2.73 percent when based on design, and 2.31 percent when related to maximum flying gross weights. Relative landing-gear weights of traditional Soviet helicopters appear to be slightly higher than those of their Western counterparts, especially as far as values based on maximum flying weights are concerned. Examination of the trend anticipated for their hypothetical machines would indicate that Soviet designers will try to have the landing gears of their helicopters as light as those in the West. With respect to different configurations, it can be seen that for the 52 m.ton gross-weight class, relatively speaking, the heaviest landing gears are expected for the side-by-side type, somewhat lighter for tandems, and lightest for single-rotor helicopters. Further investigation of Fig. 3.5 will show that the relative weight of the XCH-62A landing gear is well above the general trend, which should be expected for the crane type. More surprising is the

TABLE 3.5

EXPLICIT & RELATIVE FUSELAGE WEIGHTS

HELICOPTER	WEIGHTS				
	DESIGN GW LB	MAX. FLYING LB	FUSELAGE WT LB	RELATIVE % BASED ON:	
				DESIGN GW	MAX.FLYING GW
WESTERN					
BO-105	4442	5114	657.3	14.80	12.85
YUH-61A	15,157	19,700	1693.4	11.17 "	8.60 "
UH-60A	16,260	20,250	2284.0	14.05 "	11.28 "
CH-53E	56,000	73,500	8704.0	15.54 "	11.84 "
CH-47D	42,700	50,000	4606.0	10.79	9.21
XCH-62A	118,000	148,000	9337.6	7.91 "	6.31 "
SOVIET ACTUAL					
Mi-2	7826	8175	981.2	12.54	12.00
Mi-8	24,470	26,455	3230.3	13.20 "	12.21 "
Mi-6	89,285	93,700	13,384.4	14.98 "	14.28 "
SOVIET HYPO					
SR 15 m.ton	33,075	[38,760]	4224.8	12.77	10.90
Tand. 15 m.ton	33,075		4809.1	14.54	
SR 52 m.ton	114,660	[131,375]	11,587.3	10.11	8.82
SBS 52 m.ton	114,660	[129,210]	17,309.3*	15.10	13.40
Tand. 52 m.ton	114,660	[143,325]	15,988.8	13.94	11.54
AVERAGE VALUES				12.96	11.02

*Including outriggers

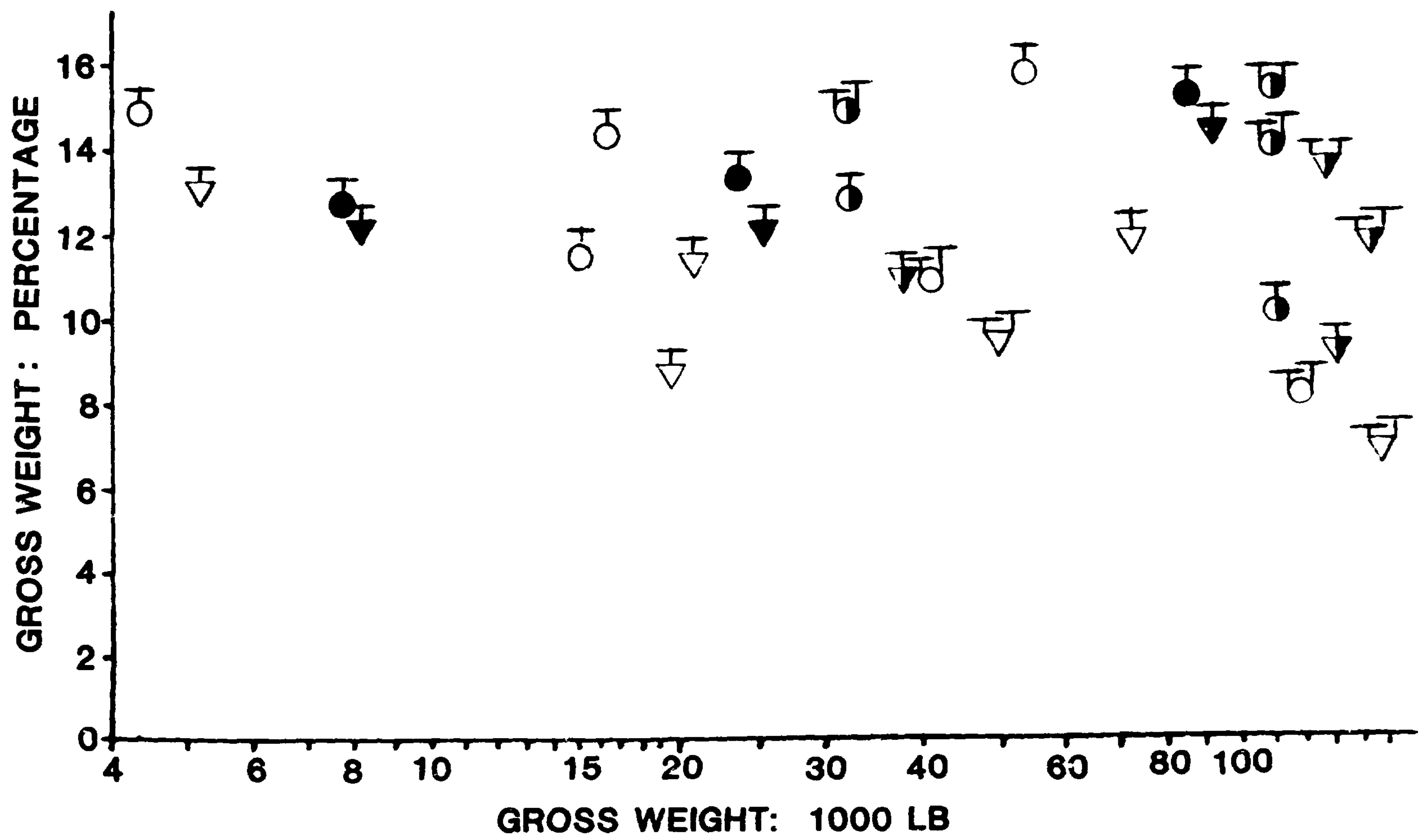


Figure 3.4 Relative weights of fuselages (body group)

TABLE 3.6

EXPLICIT AND RELATIVE LANDING-GEAR WEIGHTS

HELICOPTER	WEIGHTS				
	DESIGN GW LB	MAX. FLYING GW; LB	LANDING GEAR LB	RELATIVE % BASED ON: DESIGN GW	RELATIVE % BASED ON: MAX. FLYING WT
WESTERN					
BO-105	4442	5114	104.2	2.35	2.04
YUH-61A	15,157	19,700	464.6	3.07 "	2.36 "
UH-60A	16,260	20,250	457.6	2.81 "	2.26 "
CH-53E	56,000	73,500	1218.7	2.18 "	1.66 "
CH-47D	42,700	50,000	1124.0	2.63	2.25
XCH-62A	118,000	148,000	(6403.5)	(5.43) "	(4.32) "
SOVIET ACTUAL					
Mi-2	7826	8175	228.4	2.92	2.79
Mi-8	24,470	26,455	685.3	2.80 "	2.59 "
Mi-6	89,285	93,700	2802.6	3.14 "	2.78 "
SOVIET HYPO.					
SR 15 m.ton	33,075	[38,760]	992.3	3.00	2.56
Tand. 15 m.ton	33,075		992.3	3.00	
SR 52 m.ton	114,660	[131,375]	2381.4	2.08	1.81
SBS 52 m.ton	114,660	[129,210]	3417.8	2.98	2.65
Tand. 52 m.ton	114,660	[143,326]	2899.6	2.53	2.02
AVERAGE VALUE (excluding XCH-62A)				2.73	2.31

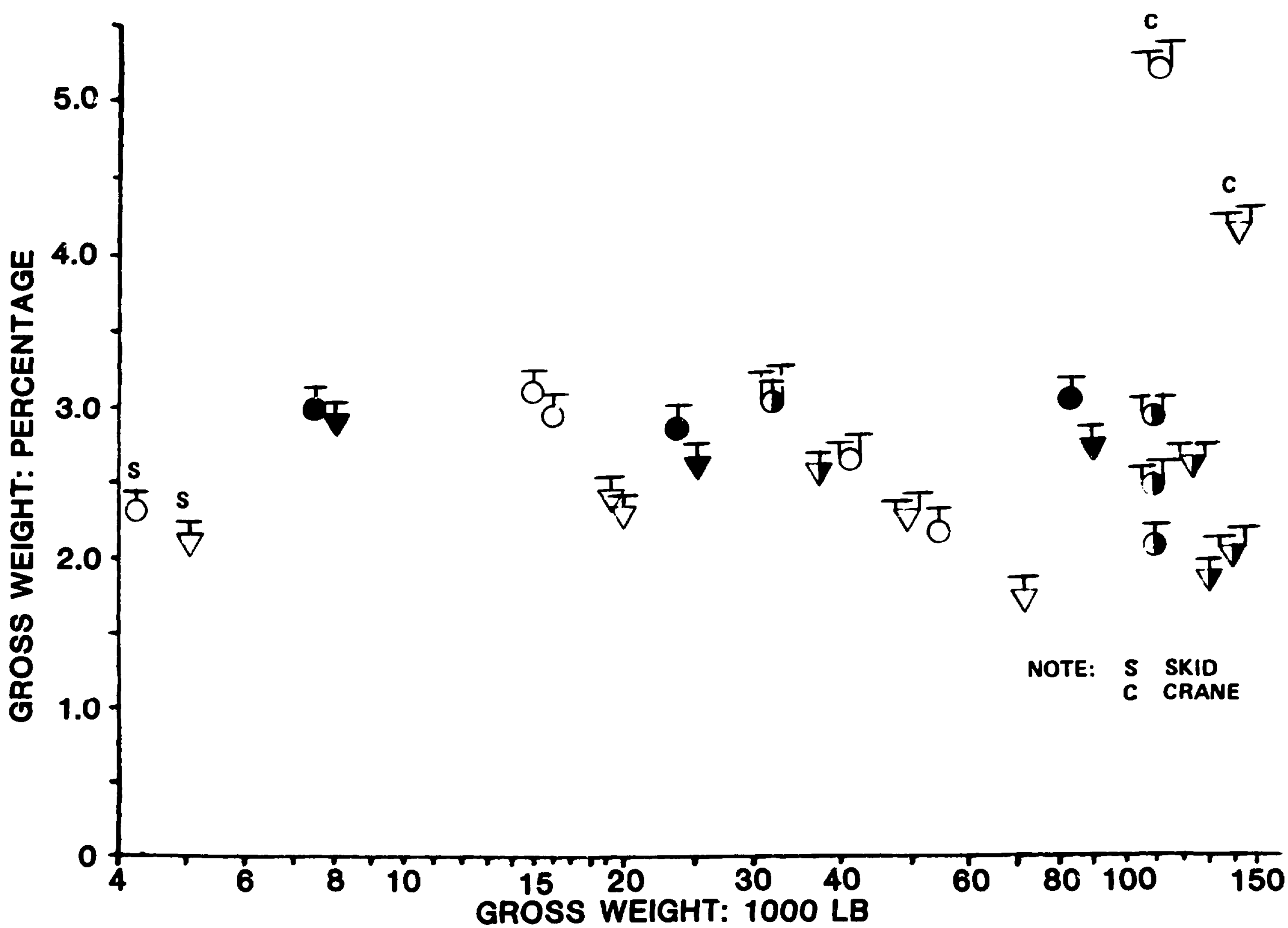


Figure 3.5 Relative landing-gear weights

lowest relative weight of 1.66 percent (based on maximum flying weight) for the CH-53E landing gear, especially when one considers that the undercarriage is retractable.

Drive System. Explicit and relative drive-system weights are shown in Table 3.7, and the relative weights are plotted in Fig. 3.6. A glance at both table and figure indicates that both the Soviet actual helicopters and their Western counterparts generally exhibit similar relative drive-systems weights – not departing very much from the average values of 9.81 percent based on design gross weight – and 8.35 percent related to maximum flying gross weights. The largest departures from the average are shown by two tandem helicopters of a similar gross-weight class; the XCH-62A exhibiting the lowest relative drive-system weight of 6.94 percent based on maximum flying gross weight, while it was indicated in Ref. 1 that the highest values of this ratio may be anticipated for the hypothetical 52 m.ton tandem (12.65 percent when referred to design gross weights, and 10.12 percent when related to maximum flying gross weights). By contrast the anticipated relative transmission system weight for the 15 m.ton hypothetical tandem, although higher by 1.33 percent than for the single-rotor machine, is still not much different than that of the CH-47D.

The large discrepancies in relative drive-system weights demonstrated for large tandems by Boeing Vertol and those visualized in Ref. 1 may be partially attributed to the assumptions by Tishchenko et al of two synchronizing shafts and a shaft rotating speed limited to 3000 rpm.

Fuel System. Explicit and relative fuel-system weights are shown in Table 3.8, while the relative weights are plotted in Fig. 3.7. It can be seen from this table that the average relative weight amounts to 1.85 percent when related to design gross weight, and 1.61 percent if based on the maximum flying gross weight.

An examination of both the table and figure will indicate a definite trend in Soviet designs – as reflected in both traditional and hypothetical helicopters – toward relative lighter fuel systems than those of their Western counterparts. For instance, for all Soviet designs – actual and hypothetical – an average relative fuel-system weight based on design would amount to 1.28 percent, and when referred to maximum flying gross weight would drop to 1.19 percent. For Western helicopters, the respective figures would be 2.60 percent and 2.11 percent. This difference can be partially explained by the application of crash-resistant self-sealing tanks in many of the examined Western designs.

Propulsion Subsystems. Table 3.9 and Fig. 3.8 provide data regarding both explicit and relative propulsion subsystem weights. It should be noted at this point that because of differences in "book-keeping" some uncertainties exist. This is especially true regarding the Soviet hypothetical helicopters. Here, after trying several approaches to determine these weights, the authors decided to use the constant coefficient of 0.05 suggested in Ref. 1 for the 52 m.ton hypothetical helicopters. Thus, the predicted kg weight of the propulsion subsystem is given as

$$W_{pss} = 0.05 N_{ref}$$

where N_{ref} is the total installed referred horsepower. No attempt was made to predict W_{pss} values for the 15 m.ton hypothetical machines.

TABLE 3.7

EXPLICIT AND RELATIVE DRIVE-SYSTEM WEIGHTS

HELICOPTER	WEIGHTS				
	DESIGN GW LB	MAX. FLYING GW; LB	LANDING GEAR LB	RELATIVE % BASED ON:	
				DESIGN GW	MAX. FLYING WT
WESTERN					
BO-105	4442	5114	435.9	9.81	8.52
YUH-61A	15,157	19,700	1793.8	11.83 "	9.11 "
UH-60A	16,260	20,250	1465.5	9.01 "	7.23 "
CH-53E	56,000	73,500	6257.1	11.17 "	8.51 "
CH-47D	42,700	50,000	4296.0	10.06	8.59
XCH-62A	118,000	148,000	10,335.5	8.76 "	6.98 "
SOVIET ACTUAL					
Mi-2	7826	8175	750.0	9.58	9.17
Mi-8	24,470	26,455	1988.0	8.12 "	7.51 "
Mi-6	89,285	93,700	8410.0	9.42 "	8.98 "
SOVIET HYPO.					
SR 15 m.ton	33,075	[38,760]	2723.2	8.23	7.03
Tand. 15 m.ton	33,075		3162.0	9.56	
SR 52 m.ton	114,660	[131,376]	10,738.4	9.37	8.17
SBS 52 m.ton	114,660	[129,210]	11,201.4	9.77	8.67
Tand. 52 m.ton	114,660	[143,326]	14,508.9	12.65	10.12
AVERAGE VALUES				9.81	8.35

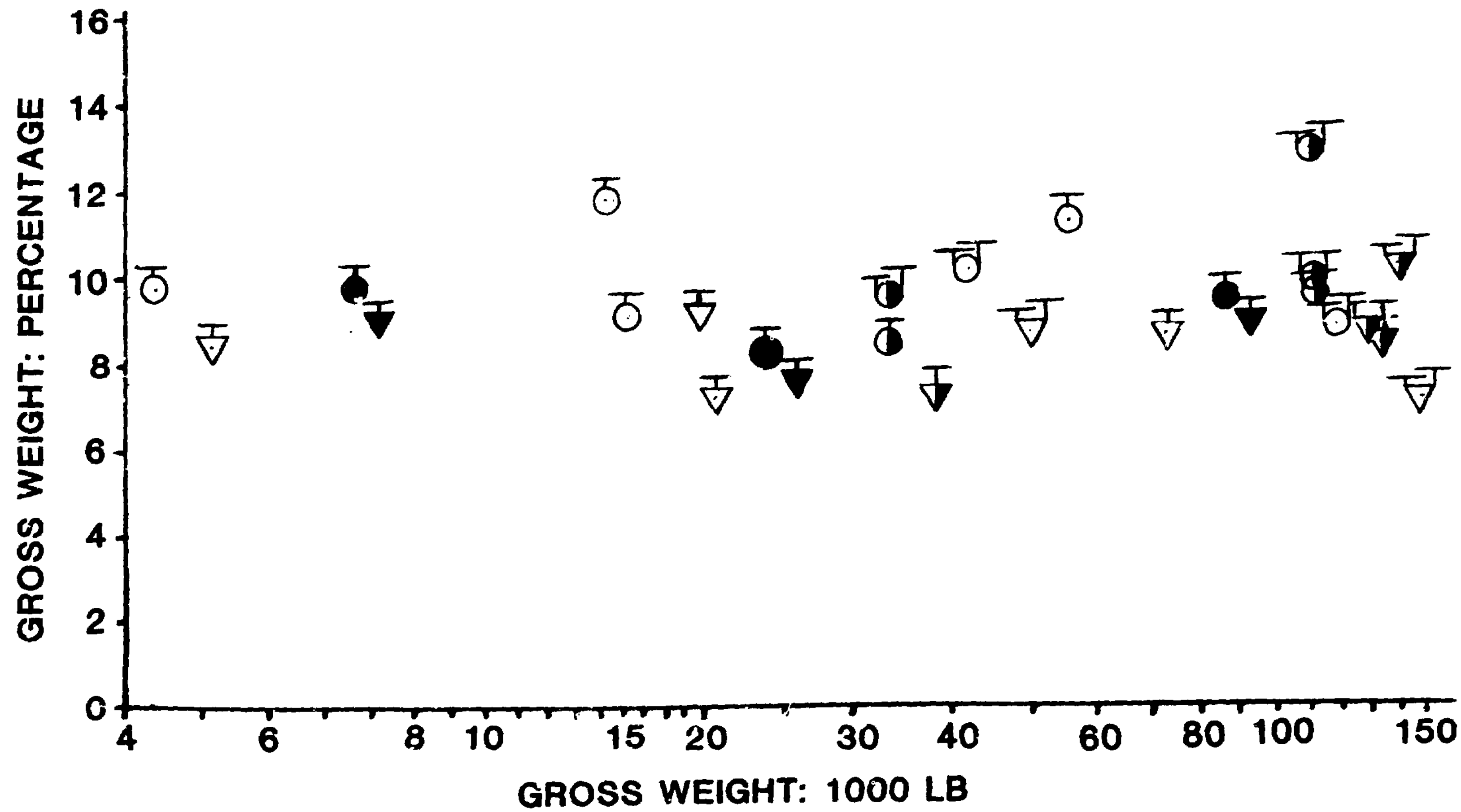


Figure 3.6 Relative drive-system weights

TABLE 3.8

EXPLICIT AND RELATIVE FUEL-SYSTEM WEIGHTS

HELICOPTER	WEIGHTS				
	DESIGN GW LB	MAX. FLYING GW; LB	FUEL SYSTEM LB	RELATIVE % BASED ON: DESIGN GW	RELATIVE % BASED ON: MAX. FLYING WT
WESTERN					
BO-105	4442	5114	67.6	1.52	1.32
YUH-61A	15,157	19,700	343.2	2.26 "	1.74 "
UH-60A	16,260	20,250	429.1	2.64 "	2.12 "
CH-53E	56,000	73,500	1225.0	2.19 "	1.67 "
CH-47D	42,700	50,000	1864.0	4.37	3.73
XCH-62A	118,000	148,000	3083.9	2.61 "	2.08 "
SOVIET ACTUAL					
Mi-2	7826	8175	79.9	1.02	0.98
Mi-8	24,470	26,455	361.3	1.48 "	1.37 "
Mi-6	89,285	93,700	1180.8	1.32 "	1.26 "
SOVIET HYPO.					
SR 15 m.ton	33,075	[38,760]	286.7	0.87	0.74
Tand. 15 m.ton	33,075		297.7	0.90	
SR 52 m.ton	114,660	[131,375]	1719.9	1.50	1.31
SBS 52 m.ton	114,660	[129,210]	1764.0	1.54	1.36
Tand. 52 m.ton	114,660	[143,325]	1861.0	1.62	1.30
AVERAGE VALUES				1.85	1.61

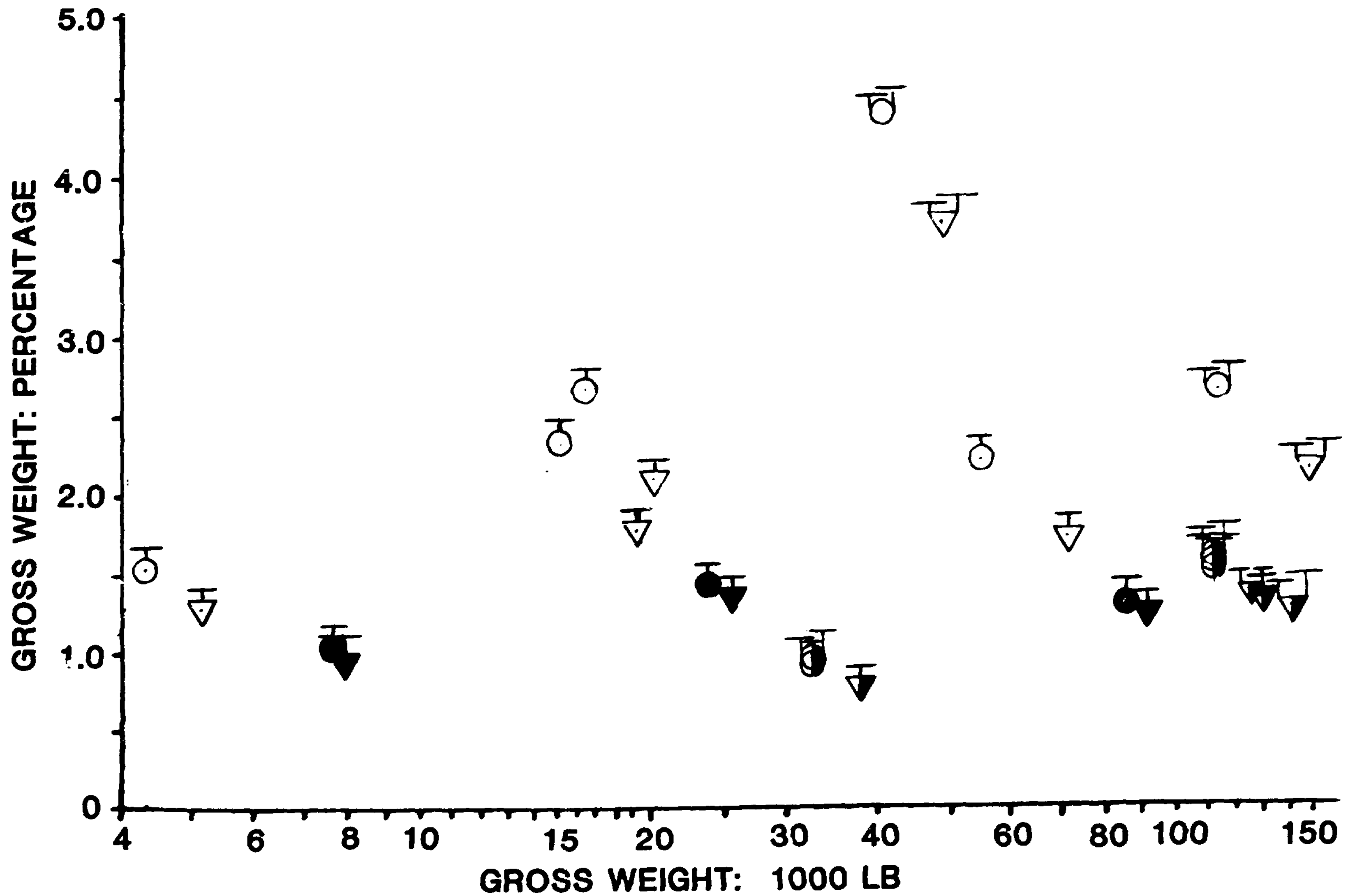


Figure 3.7 Relative fuel-system weights

TABLE 3.9

EXPLICIT AND RELATIVE PROPULSION SUBSYSTEM WEIGHTS

HELICOPTER	WEIGHTS						
	DESIGN GW LB	MAX. FLYING GW; LB	PROPULSION SUBSYSTEM LB	RELATIVE % BASED ON:			
				DESIGN GW		MAX. FLYING WT	
WESTERN							
BO-105	4442	5114	56.5	1.27		1.10	
YUH-61A	15,157	19,700	116.3	0.77	"	0.59	"
UH-60A	16,260	20,250	143.5	0.88	"	0.71	"
CH-53E	56,000	73,500	630.3	1.13	"	0.86	"
CH-47D	42,700	50,000	243.0	0.57		0.49	
XCH-62A	118,000	148,000	812.5	0.69	"	0.55	"
SOVIET ACTUAL							
Mi-2	7826	8175	198.5	2.53		2.43	
Mi-8	24,470	26,455	297.7/458.6	1.22/1.89	"	1.13/1.73	"
Mi-6	89,285	93,700	1777.2	1.99	"	1.90	"
SOVIET HYPO.							
SR 15 m.ton	33,075	[38,760]	–	–		–	
Tand. 15 m.ton	33,075	–	–	–		–	
SR 52 m.ton	114,660	[131,375]	[2480]	2.16		1.88	
SBS 52 m.ton	114,660	[129,210]	[2137]	1.86		1.65	
Tand. 52 m.ton	114,660	[143,325]	[2412]	2.10		1.68	
AVERAGE VALUES				1.47		1.28	

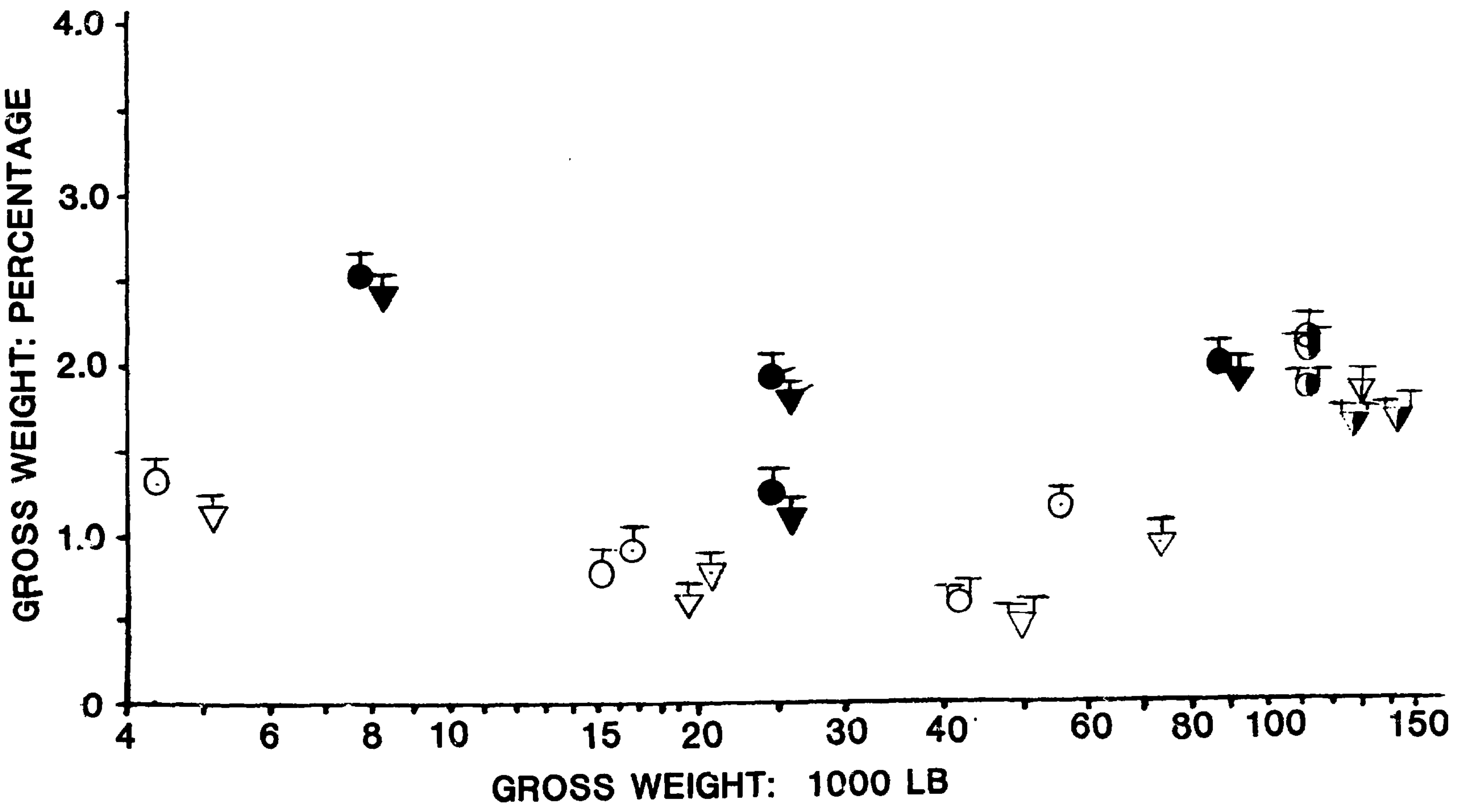


Figure 3.8 Relative propulsion subsystem weights

It can be seen from both table and figure that while the average relative weight values amount to 1.47 percent for normal and 1.28 percent for maximum flying gross weights, large deviations from these averages are encountered. It appears that, in general, Soviet helicopters indicate higher relative weight values than for Western helicopters, but this apparent trend may reflect the differences in the bookkeeping methods as much as basic differences in design philosophy. It should be added that because of the relatively small contributions of this particular system to the gross weight of the helicopter, existing differences between individual helicopters and groups of helicopters have no significant effect on the overall weight picture.

Flight-Control Group. Looking at Table 3.10 and Fig. 3.9 wherein data on the relative flight-control group weights are presented, one would note that the average relative weight values are 4.42 percent when based on design gross weight, and 3.74 percent when referred to maximum flying gross weight. One may also determine from Fig. 3.9 that with the exception of the Mi-6, the general trend is toward a decrease in the relative flight-control group weight as the size of the helicopter increases. At this point, the relative flight-control group weights for the UTTAS-type helicopters when referred to their design gross weight appear higher than indicated by the general trend. However, when maximum flying gross weight is taken as a basis, the differences disappear. With respect to various configurations, it can be seen that the lowest relative flight-control group weights are anticipated for the hypothetical side-by-side 52 m.ton helicopter. In regard to tandems, the CH-47D and the XCH-62A show relative control weight values close to the average, while for the hypothetical 15 m.ton gross-weight class configuration, higher than average relative weights are anticipated. These values are even higher when compared with single-rotor helicopters of the same gross-weight class. By contrast, for the 52 m.ton hypothetical tandem, lower than average relative weights are foreseen – even lower than those of the XCH-62A. Slightly lower relative control weights are predicted for the single-rotor hypothetical 52 m.ton helicopters than for the hypothetical tandems. These weights are quite close to those of the CH-53E and show the lowest relative control-weight values of all the compared helicopters.

3.3 Relative Major Component Weight Trends for Various Configurations

General. As a supplement to the detailed discussion in Section 3.2, it should be of interest to indicate (a) how the relative weights of the major components vary between configurations, and (b) how the Soviet and Western schools of design visualize those changes.

In order to accomplish this task, the average values of the relative weights for the previously considered major helicopter components are computed for the following configuration groups: (1) Western single-rotor, (2) Western tandems, (3) Soviet traditional single-rotor, (4) Soviet hypothetical single-rotor, (5) Soviet hypothetical side-by-side, and (6) Soviet hypothetical tandems. The results of calculations are shown numerically in Tables 3.11 through 3.14, and graphically presented in Figs. 3.10 through 3.13.

TABLE 3.10

EXPLICIT & RELATIVE FLIGHT-CONTROL GROUP WEIGHTS

HELICOPTER	WEIGHTS				
	DESIGN GW LB	MAX. FLYING LB	FLIGHT CONTROLS LB	RELATIVE % BASED ON:	
				DESIGN GW	MAX. FLYING GW
WESTERN					
BO-105	4442	5114	217.9	4.91	4.26
YUH-61A	15,157	19,700	912.[illegible]	6.02 "	4.63 "
UH-60A	16,260	20,250	834.5	5.13 "	4.12 "
CH-53E	56,000	73,500	1658 1	2.96 "	2.26 "
CH-47D	42,700	50,000	1766	4.14	3.53
XCH-62A	118,000	148,000	5485	4.65 "	3.11 "
SOVIET ACTUAL					
Mi-2	7826	8175	350.1	4.47	4.28
Mi-8	24,470	26,455	1068.6	4.37 "	4.04 "
Mi-6	89,285	93,700	5479.4	6.14 "	5.85 "
SOVIET HYPO.					
SR 15 m.ton	33,075	[38,760]	1342.8	4.06	3.46
Tand. 15 m.ton	33,075		1675.6	5.07	
SR 52 m.ton	114,660	[131,375]	3638.3	3.17	2.77
CBS 52 m.ton	114,660	[129,210]	3307.5	2.88	2.56
Tand. 52 m.ton	114,660	[143,325]	4520.3	3.94	3.15
AVERAGE VALUES				4.42	3.68

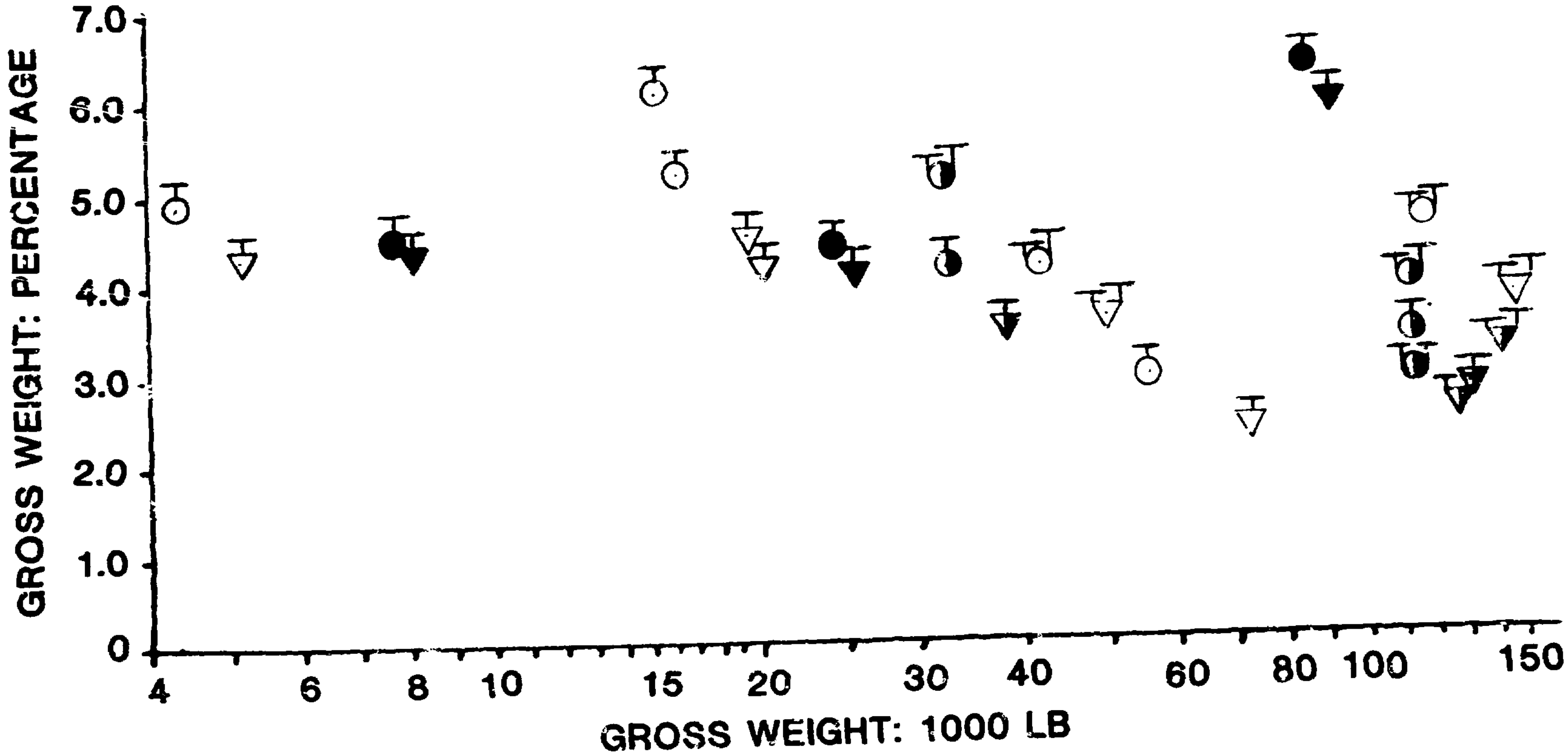


Figure 3.9 Relative weights of flight control group

Before discussing the trends shown by the above-mentioned tables and graphs, it should be emphasized that from a statistical viewpoint, the width of the data base is somewhat limited, as often only two elements appear in a group. Nevertheless, it is believed that in spite of these limitations—suggesting the use of caution when interpreting the results—some valuable insight can be gained regarding the fractional portion of gross weight that a given major component tends to represent in various helicopter configurations. Furthermore, it would be possible to find out the extent to which Soviet and Western schools of helicopter design differ in that respect. Finally, by examining these trends for Soviet hypothetical machines, one can learn why in Ref. 1, rightly or wrongly, the configuration ratings for the medium to heavy-lift helicopters were obtained.

Dynamic System (Blades, Hubs and Hinges, and Drive System. The average relative-weight values for main-rotor blades based on design and maximum flying gross weights as computed from Table 3.2 for the six configurations considered here are shown in Table 3.11, and graphically presented on the left-hand side of Fig. 3.10.

TABLE 3.11

AVERAGE RELATIVE MAIN-ROTOR BLADE WEIGHTS

TYPE	AVERAGE VALUES, %	
	DESIGN GW	MAX. FLYING GW
Western Single-Rotor	5.53	4.44
Western Tandem	5.15	4.25
Soviet Traditional Single-Rotor	6.26	5.90
Soviet Hypothetical Single-Rotor	5.23	4.53
Soviet Hypothetical Side-by-Side	4.04	3.58
Soviet Hypothetical Tandem	5.90	5.34

A glance at the figure and table indicates that there is little difference between the relative blade weights of the Western single-rotor and tandem helicopters, although the tandems appear to be a shade lighter.

The relative blade weights of the Soviet single-rotor helicopters of "traditional design" appear to be considerably heavier than their Western counterparts by a factor of about 1.35 when using the maximum flying gross weight as a basis. However, judging from the figures for the hypothetical machines, the Soviet designers apparently expect to approach the Western level in their new single-rotor helicopters, and do even better in the side-by-side configurations. In contrast with this optimism, and contrary to the Western trend, they expect that the relative weights of their tandems will be higher $[\Delta(W_{bl}/W_{gr_{des}})_t \approx 0.36\%]$ than those of new single-rotor helicopters.

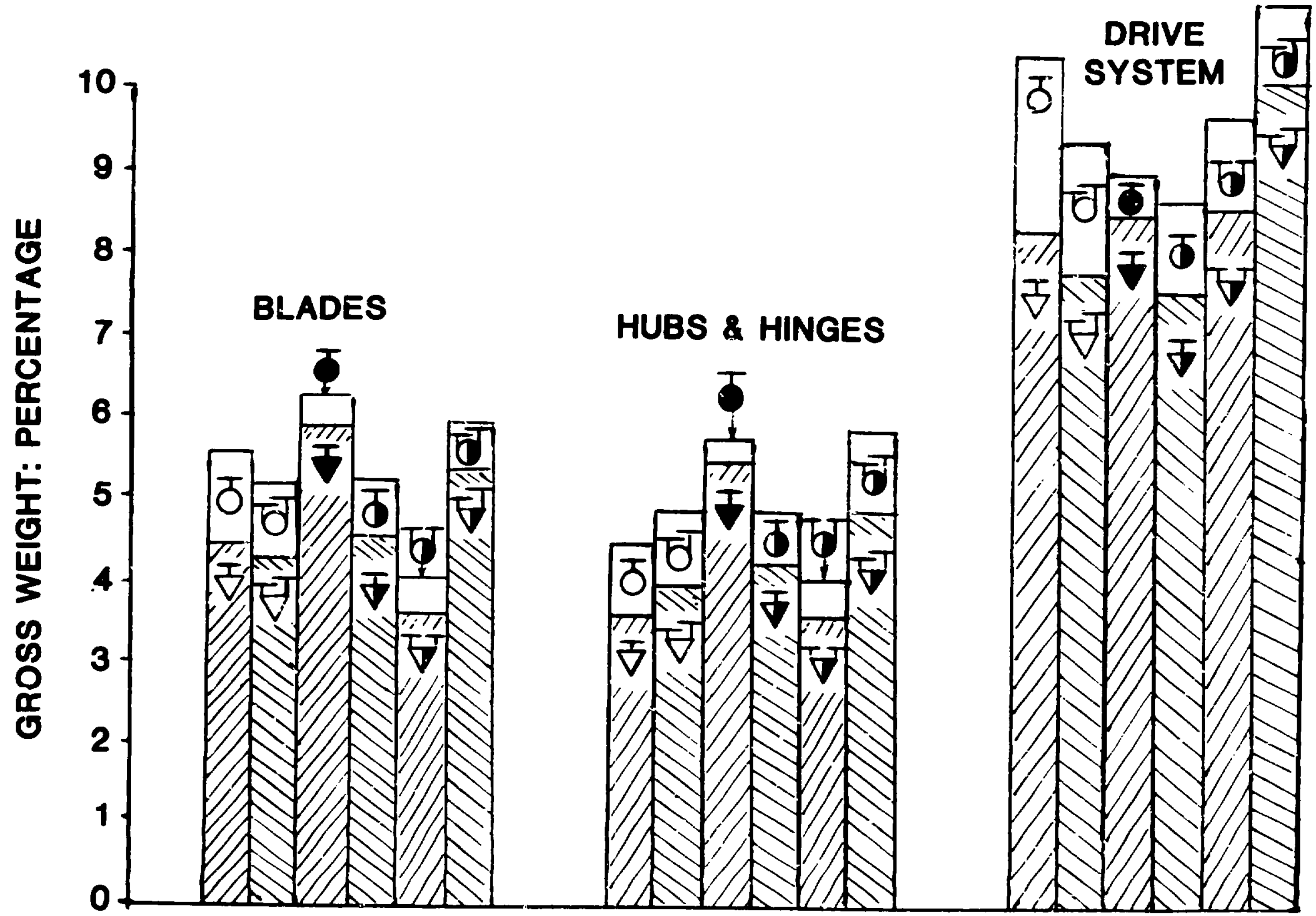


Figure 3.10 Trends in relative weights of major dynamic-system components

The average relative weight values for hubs and hinges are given in Table 3.12, and graphically shown in the central portion of Fig. 3.10.

TABLE 3.12

AVERAGE RELATIVE MAIN-ROTOR HUB & HINGE WEIGHTS

TYPE	AVERAGE VALUES, %	
	DESIGN GW	MAX. FLYING GW
Western Single-Rotor	4.47	3.57
Western Tandem	4.88	4.00
Soviet Traditional Single-Rotor	5.79	5.47
Soviet Hypothetical Single-Rotor	4.83	4.18
Soviet Hypothetical Side-by-Side	4.04	3.58
Soviet Hypothetical Tandem	5.85	4.85

As in the preceding case there is very little difference in the relative weights of hubs and hinges of Western single-rotor and tandem configurations although, in this case, those of the tandem appear to be a shade heavier.

The relative weights of the Soviet traditional single-rotor helicopters are considerably heavier than those of their Western counterparts, especially when related to maximum flying weight. Again, as in the case of blades, trends depicted by the hypothetical helicopters indicate that in the single-rotor configurations, Soviet designers expect to approach the relative weight levels of Western hubs and hinges. Projections for side-by-side configurations are even more optimistic than for single-rotors.

With respect to tandems, here again, considerably higher values of relative hub and hinge weights are expected than for single-rotor configurations. Furthermore, these anticipated weight increases are much greater than those depicted by the Western trends.

Drive system relative weights derived from Table 3.7 are shown in Table 3.13, and graphically presented on the right-hand side of Fig. 3.10.

As shown in this table, the relative drive system weights for Western single-rotor configurations are somewhat higher than those for tandems. It is also interesting to note that Soviet traditional single-rotor helicopters exhibit relative drive system weights slightly lower (by a factor of 0.86) than their Western counterparts when using the design gross weight as a reference, but the situation is reversed when maximum flying gross weight is used.

A study of the relative drive-system weight trends for Soviet helicopters would show only slightly lower weights for hypothetical single-rotor helicopters than for traditional machines when using design

TABLE 3.13

AVERAGE RELATIVE DRIVE-SYSTEM WEIGHTS

TYPE	AVERAGE VALUES, %	
	DESIGN GW	MAX. FLYING GW
Western Single-Rotor	10.46	8.34
Western Tandem	9.41	7.79
Soviet Traditional Single-Rotor	9.04	8.55
Soviet Hypothetical Single-Rotor	8.80	7.60
Soviet Hypothetical Side-by-Side	9.77	8.67
Soviet Hypothetical Tandem	11.11	10.12

gross weight as a reference, but when related to maximum flying gross weights, noticeably lower values are expected for the hypothetical designs than for existing traditional machines.

Somewhat higher relative drive-system weights are forecast for the hypothetical side-by-side configurations than those of traditional design. With respect to tandems, contrary to the experience in Western design .e Soviet relative drive-system weights are much higher than for traditional machines.

Fuselage and Landing Gears. Fuselage (body group) and landing gears are considered together, as they represent the most important elements of the helicopter static airframe, with the fuselage taking a larger percentage of the helicopter gross weight.

Numerical data regarding the average relative fuselage weights are given in Table 3.14, while the graphical presentation is on the left-hand side of Fig. 3.11. It can be seen from these sources that within

TABLE 3.14

AVERAGE RELATIVE FUSELAGE (BODY GROUP) WEIGHTS

TYPE	AVERAGE VALUES, %	
	DESIGN GW	MAX. FLYING GW
Western Single-Rotor	13.89	11.14
Western Tandem	9.35	7.76
Soviet Traditional Single-Rotor	13.58	12.83
Soviet Hypothetical Single-Rotor	11.44	9.86
Soviet Hypothetical Side-by-Side	15.10	13.40
Soviet Hypothetical Tandem	14.24	11.54

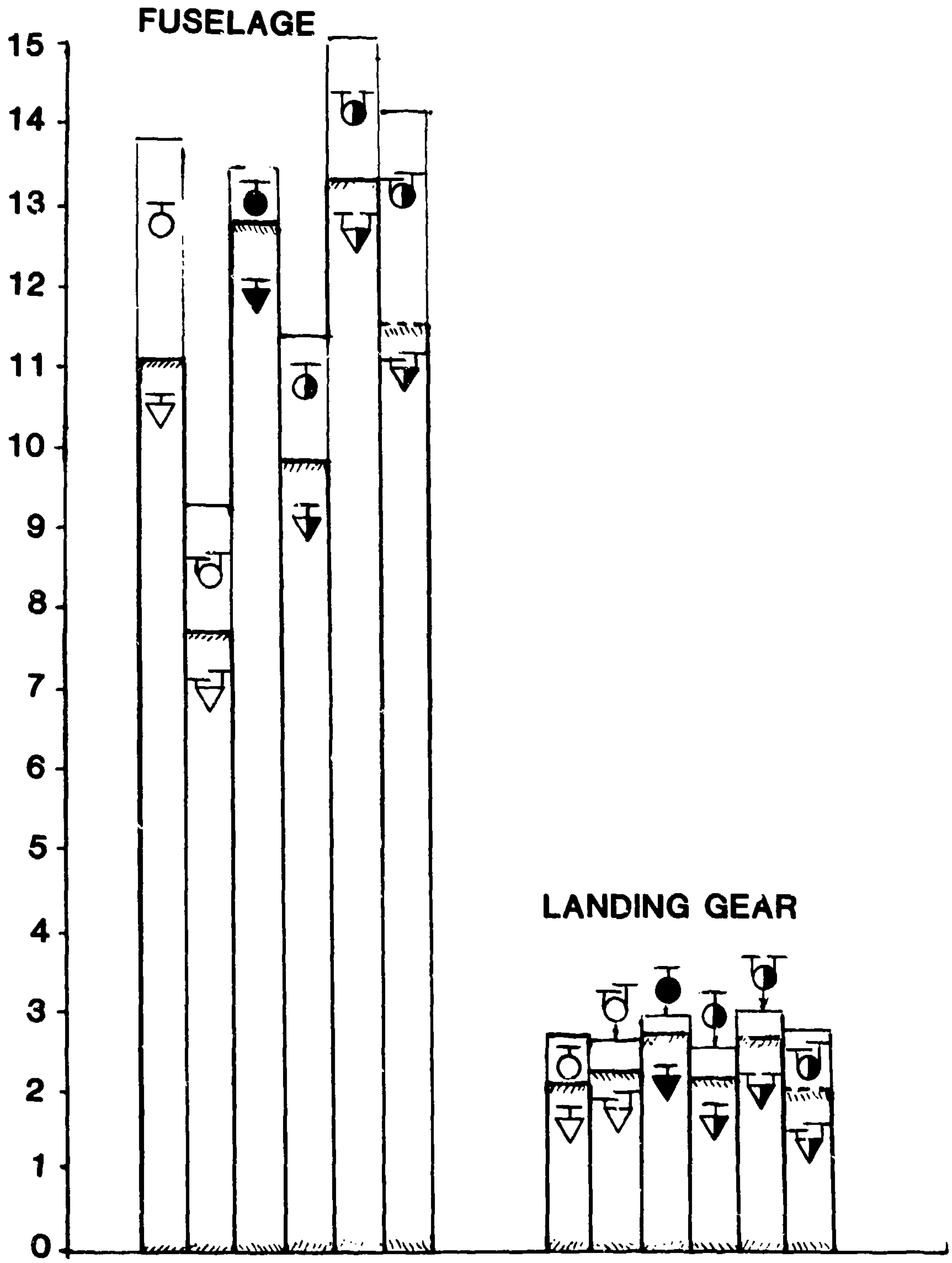


Figure 3.11 Trends in relative weights of fuselages and landing gears

the Western school of design, the relative weights of tandem fuselages appear to be much lower than those of single-rotor configurations.

With respect to Soviet traditional designs, one should note that the relative fuselage weights of single-rotor helicopters are a shade lower than for their Western counterparts when design gross weight is taken as a basis for the comparison, and somewhat higher (by a factor of 1.15) when relative weights are referred to maximum flying gross weights.

It is apparent that the Soviet designers of hypothetical single-rotor configurations expect to achieve lower relative fuselage weights than those for the same configuration now existing in the West.

For side-by-side types, much higher relative fuselage weights are expected (by a factor of 1.35) than for the hypothetical single-rotor helicopters. This trend is justified by the inclusion of the outriggers and main gearbox attachments in the fuselage weight.

In their hypothetical tandems, Soviet designers anticipate, again in contrast to the actual trend in the West, higher relative fuselage weights (by a factor of 1.25) than their hypothetical single-rotor helicopters.

Landing-gear data is presented in Table 3.15, and on the right-hand side of the graph in Fig. 3.11.

TABLE 3.15

AVERAGE RELATIVE LANDING-GEAR WEIGHTS

TYPE	AVERAGE VALUES, %	
	DESIGN GW	MAX. FLYING GW
Western Single-Rotor*	2.67	2.09
Western Tandem**	2.63	2.25
Soviet Traditional Single-Rotor	2.95	2.72
Soviet Hypothetical Single-Rotor	2.54	2.19
Soviet Hypothetical Side-by-Side	2.98	2.65
Soviet Hypothetical Tandem	2.77	2.02

*Excluding BO-105

**Excluding XCH-62A

One can see from these inputs that when exceptional designs such as the crane-type L/G of the XCH-62A and the skid gear of the BO-105 are excluded, there is, in general, no significant difference in the relative undercarriage weight between the considered configurations representing both Western and Soviet designs.

Flight-Control and Tail-Rotor Groups. Flight-control and tail-rotor groups are considered together, as, in essence, the tail rotor also serves as a means for helicopter control.

Numerical and graphical data regarding average values of the relative flight-control group is shown in Table 3.16 and on the left-hand side of Fig. 3.12, and for the tail-rotor group is given in Table 3.17 and on the right-hand side of Fig. 3.12.

TABLE 3.16

AVERAGE RELATIVE FLIGHT-CONTROL GROUP WEIGHTS

TYPE	AVERAGE VALUES, %	
	DESIGN GW	MAX. FLYING GW
Western Single-Rotor	4.76	3.82
Western Tandem	4.40	3.62
Soviet Traditional Single-Rotor	4.99	4.74
Soviet Hypothetical Single-Rotor	3.47	3.12
Soviet Hypothetical Side-by-Side	2.88	2.56
Soviet Hypothetical Tandem	4.51	3.60

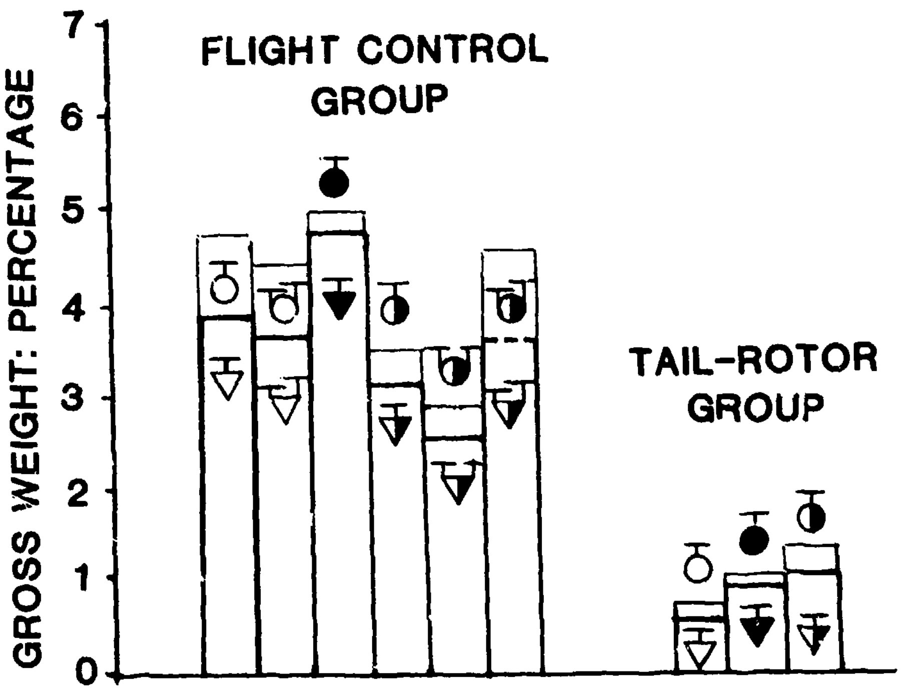


Figure 3.12 Flight-control & tail-rotor group relative-weight trends

TABLE 3.17

AVERAGE RELATIVE TAIL-ROTOR GROUP WEIGHTS

TYPE	AVERAGE VALUES, %	
	DESIGN GW	MAX. FLYING GW
Western Single-Rotor	0.71	0.57
Soviet Traditional Single-Rotor	1.01	0.95
Soviet Hypothetical Single-Rotor	1.27	1.10

One may determine from the above data that the contribution of the tail-rotor group to the helicopter gross weight is small, as it hardly exceeds one percent of the maximum flying gross weight. In contrast, the role of the flight-control group in that respect is more significant as, in many cases, it constitutes more than four percent of the gross weight.

One would find that in Western designs there is not much difference in the relative weight of the flight-control group between single-rotor and tandem configurations, although for the tandem the relative weights appear a shade lower.

The relative flight-control weights of Soviet traditional single-rotor helicopters are somewhat higher (especially when based on maximum flying gross weights) than for their Western counterparts.

As far as Soviet hypothetical helicopters are concerned, relative weight levels considerably lower than for the traditional Soviet single-rotor design and also lower than in the West are forecast in Ref. 1. The lowest weights are visualized for the side-by-side, and the highest for the tandem configurations. With respect to the tandem, here again the trend indicated in Ref. 1 is contrary to the actual experience in the West.

A closer look at Soviet weight trends would indicate that tail-rotor group weights for traditional helicopters are higher by a factor of about 1.42 for design and 1.67 for maximum flying weights than for Western designs. Still slightly higher values are predicted for hypothetical helicopters.

Fuel System and Propulsion Subsystem. The fuel system and propulsion subsystems are grouped together, as both represent components of a larger power system. Although percentile contribution of either to the gross weight of the helicopter is relatively small (about 1.61 to 1.85 percent for the fuel system, and about 1.39 percent to 1.61 percent for the propulsion subsystem), it is still significant enough to deserve some attention regarding the relative weight trends.

With respect to the fuel system, it can be noted from Table 3.18 and the graph on the left side of Fig. 3.13 that, in general, Western fuel installations are relatively heavier than Soviet ones—probably because of the wide use of self-sealing, crash-resistant tanks. It should also be noted that the relative fuel-system weights of Western tandems are considerably higher (by factors of about 1.62 to 1.70) than those of the single-rotor configurations.

TABLE 3.18

AVERAGE RELATIVE FUEL-SYSTEM WEIGHTS

TYPE	AVERAGE VALUES, %	
	DESIGN GW	MAX. FLYING GW
Western Single-Rotor	2.15	1.71
Western Tandem	3.49	2.91
Soviet Traditional Single-Rotor	1.27	1.20
Soviet Hypothetical Single-Rotor	1.62	1.40
Soviet Hypothetical Side-by-Side	1.54	1.36
Soviet Hypothetical Tandem	1.71	1.50

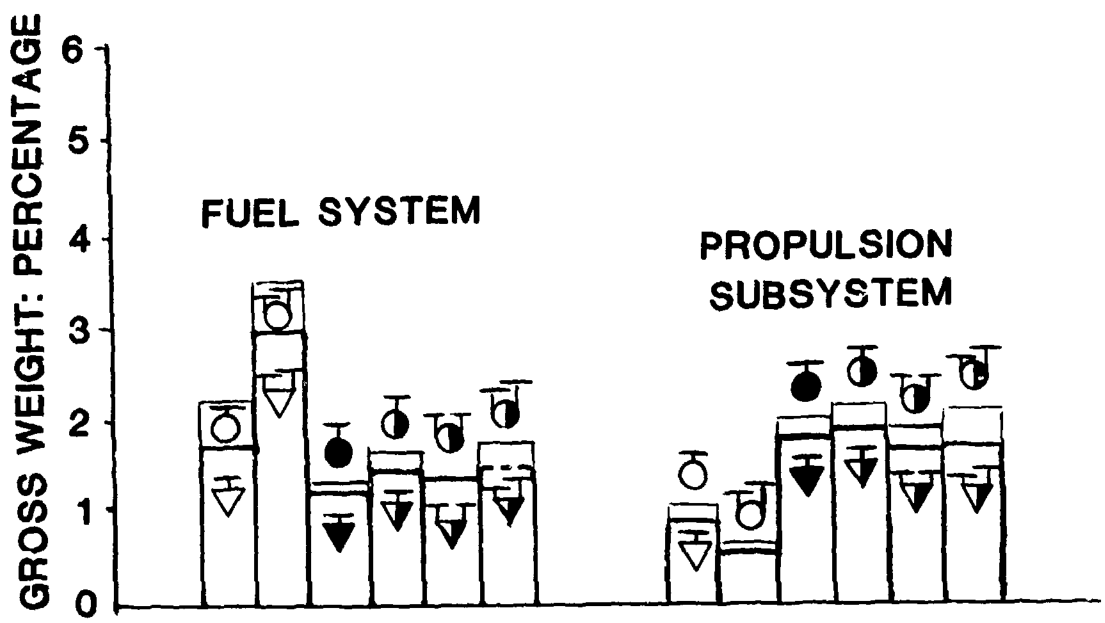


Figure 3.13 Fuel system and propulsion subsystem relative weight trends

Soviet traditional designs exhibit the lowest relative fuel-system weight levels of that group; however, slightly higher values for the hypothetical helicopters are foreseen in Ref. 1, the highest of them being for the tandem – this time in agreement with the Western trend.

It should be emphasized that the relative weight trends of propulsion subsystems should be treated with caution since, as indicated previously, differences may exist between Western and Soviet approaches as to what constitutes propulsion subsystems. Furthermore, looking at Table 3.19, one should note that the figures related to Soviet hypothetical helicopters represent single data points. Keeping these reservations in mind, the following determinations were made from the data contained in Table 3.19 and the right side of Fig. 3.13.

TABLE 3.19

AVERAGE RELATIVE PROPULSION SUBSYSTEM WEIGHTS

TYPE	AVERAGE VALUES, %	
	DESIGN GW	MAX. FLYING GW
Western Single-Rotor	1.01	0.82
Western Tandem	0.63	0.52
Soviet Traditional Single-Rotor	1.91	1.78
Soviet Hypothetical Single-Rotor*	2.16	1.88
Soviet Hypothetical Side-by-Side*	1.86	1.65
Soviet Hypothetical Tandem*	2.10	1.68

*Single-point data

There seems to be a slight difference in the relative weights of the propulsion subsystems of Western single-rotor and tandem helicopters (the latter being a little lighter), while for all Soviet helicopters – both traditional and hypothetical – the differences appear insignificant. Furthermore, the relative weights of the propulsion subsystems of Soviet helicopters generally appear higher than those of the West; but this may be more the result of different approaches in weight bookkeeping than differences in design. Finally, it should be realized that contribution of the propulsion subsystem to the overall gross weight of the aircraft is quite small; hence, a misjudgement of the relative weight trend for this particular component would have little effect on the overall helicopter weight picture.

3.4 Maintenance Comparison – Soviet and Western Helicopters

<u>Introduction</u>. In contemplating this section, it was originally hoped that sufficient information on "systems" costs of Soviet helicopters would be found to permit a fairly comprehensive side-by-side review of the usual economic factors. The reality was that the only quantified data was for one light,

general purpose, twin-engine Soviet design, the Mi-2, which has been produced in Poland since its prototype days. However, additional evidence of the nature of Soviet maintenance trends was derived from such sources as Ref. 1, and from reports and discussions with Eastern bloc helicopter experts. The major contributors and acknowledgements are listed at the conclusion of this section. The results which follow therefore provide a fairly sharply-drawn contrast between the Mi-2 and its Western counterpart, the Messerschmitt-Bolkow-Blohm (MBB) BO-105, attenuated by a somewhat philosophical discussion of the cause and effect of this contrast and possible changes in Soviet attitudes toward design for maintenance. In view of the sparse data on actual maintenance characteristics of Soviet helicopters and frequent dichotomy between sources, it was decided to present the results in three parts: Part (1) provides a tabulated comparison of the best available information on the Soviet Mi-2 and its closest Western counterpart, the MBB BO-105, since both designs originated in the early 1960's. Charts are also given showing the maintenance parameters of a range of Western helicopters and the Mi-2, with maximum flying gross weights indicated. Part (2) reviews Petroleum Helicopter's Inc.'s evaluation of the Mi-10. Part (3) attempts to explain the differences in design for maintenance displayed in Parts (1) and (2), and to project the likely trends that may be expected from current Soviet attitudes toward design for maintenance.

Maintainability of the Mi-2 vs. Western Helicopters. Table 3.20 and Fig. 3.14 show how the Soviet-designed Mi-2 compares with an array of Western designs, but particularly the MBB BO-105 which, although slightly smaller, has approximately the same power and mission. Both table and figure illustrate the superior overhaul tours and/or the retirement life of four major components (main-rotor blades, rotor transmission, main-rotor head, and engines). Note that while the designs are all contemporary, Western helicopters have achieved longer overhaul tours and a dramatic difference in main-rotor blade retirement life. Even the initial values for the civil version of the Boeing Vertol Chinook are 50 percent higher than those attained by the Mi-2 after 15 years of service.

It should be noted at this point that private talks with representatives of PZL Swidnik indicated that from a strictly technical viewpoint, it would be possible to increase the retirement life of the main-rotor blades to at least 1800 hours. However, the licenser; i.e., the Soviet Mil Design Bureau, objected to that move. The cause for the objection may have stemmed from special socio-economic conditions for operation of the helicopter industry in the USSR. For instance, actual blade manufacture is performed in separate factories wherein incentives exist to increase originally established quotas. Consequently, a large surplus of blades may develop, making it more attractive to simply discard a blade after a relatively low number of flight hours than to overhaul it, as well as to go through all the procedures required for extending its time between overhauls (TBO) and component life.

Petroleum Helicopters Inc. – Experience with Mi-10. One of the first sources considered for information on Soviet helicopter maintenance was Louisiana-based Petroleum Helicopters, Inc. (PHI). Not only is PHI one of the largest commercial operators in the Free World, but the company is known to have operated at least two of the Mil designs. They submitted a reprint from Vertiflight[8]

TABLE 3.20

MAINTAINABILITY COMPARISON CHART

DESIGNER	Mil	MBB	AEROSPATIALE	BOEING-VERTOL	BOEING-VERTOL
MODEL	Mi-2(1)	BO-105	SA 330J	BV-107(2)	CH-47D(3)
TYPE	General Purpose	General Purpose	Transport	Transport	Transport
FIRST FLIGHT	1961	1964	1965	1962	1961
NUMBER IN SERVICE	3000	1000+	700	800	1000
GROSS WEIGHT; LB	8175	5114	16,315	23,300	50,000
POWERPLANT	(2) ISOTOV/PZL @ 400 shp	(2) Allison @ 420 shp	(2) Turbomeca @ 1575 shp	(2) GE T-58 @ 1870 shp	(2) Lycoming @ 3750 shp
MAIN-ROTOR RADIUS; FT	23.88	16.14	24.6	25.5	30.0
MAINTENANCE DATA					
Overhaul Tours – hr					
Main Transmission	1000	1600	3000	2000	1500
Rotor Head	1000	10,000	2000	2500	1500
Engine	1000	3500	2000	4000	1500
Retirement life – hr					
Main-Rotor Blades	1000	10,000	–	30,000	INF. LIFE
Approximate Price – $	500,000	830,000	–	5,000,000	10,000,000

NOTES:

(1) The Mi-2, although designed by the Mil Bureau in the USSR, has been produced only in Poland by PZL-Swidnik. The maintenance manual for the Mi-2 states, "The safe fatigue life of the helicopter amounts to 8000 flying hours." This is in marked contrast to Western practice as exemplified by the BV-107 for instance, which has achieved in excess of 20,000 hours as operated by Columbia Helicopters, Inc.

(2) Elsewhere in this document the BV-107 is designated the CH-46E; however, the maintenance parameters are those of the civil version, the BV-107.

(3) Maintenance parameters are for the civil version, the BV-234.

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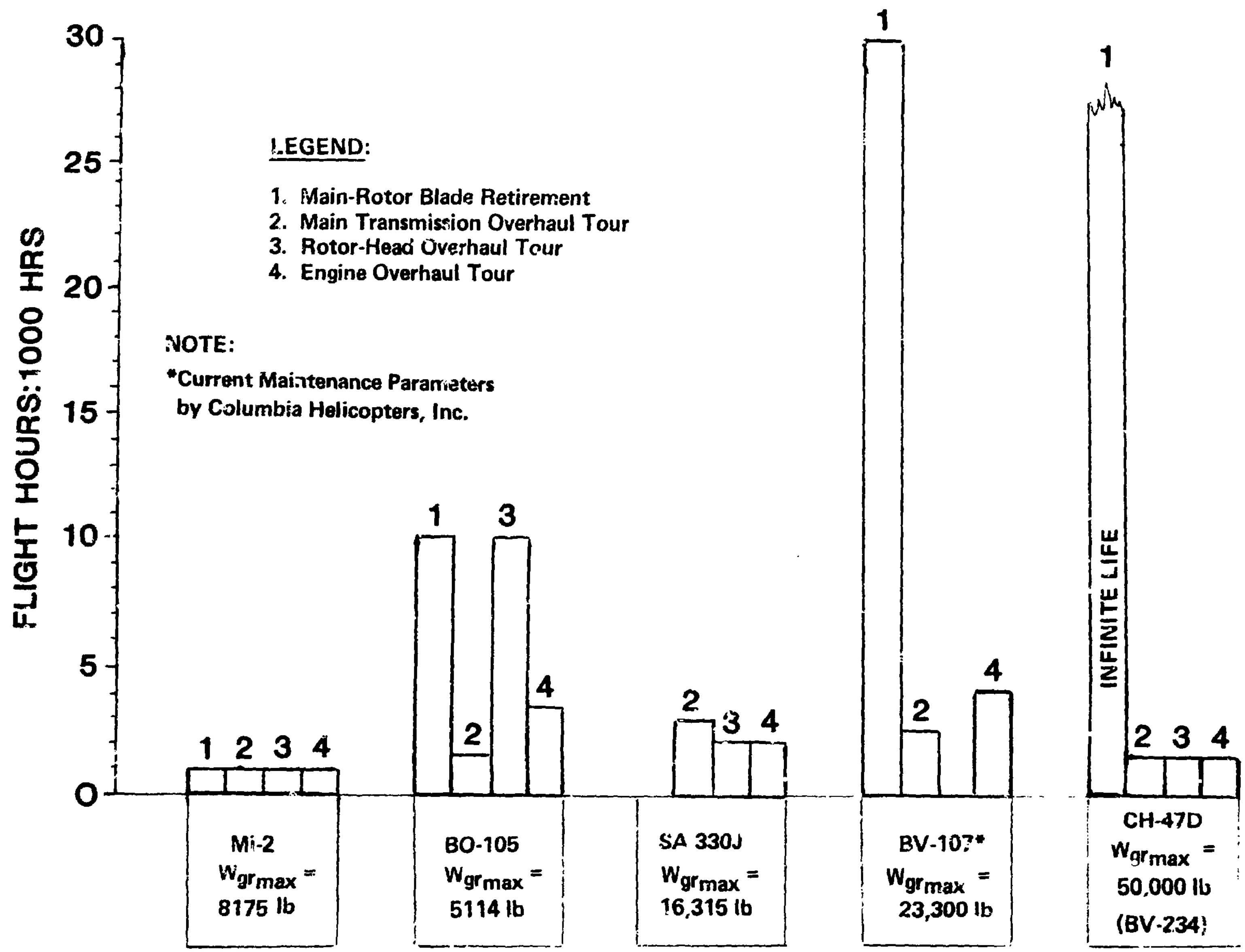


Figure 3.14 Maintenance data for Soviet Mi-2 and selected Western helicopters

describing the company's experience with the Soviet Mi-10 during an 'evaluation' project (the Mi-8 was also operated, but the article does not discuss this smaller helicopter).

While the calendar time over which the evaluation was conducted was not disclosed, the actual flying time is described as "hundreds of hours," probably no more than a year's utilization in external load operations — the prime mission of the Mi-10.

Marks given on field maintainability were favorable, with emphasis on "ease of access " There can be no doubt that the operator was greatly impressed by the care taken by Soviet designers to provide a helicopter that proved to be self sustaining in "frontier land, the natural habitat of the helicopter." It was suggested that the benefits in field maintenance and reliability may have been gained "at the expense of a little weight" resulting from the design objective of "simplification rather than sophistication." In connection with the weight penalty observation by PHI, it is interesting to note that at the time of the evaluation, the Boeing Vertol Chinook helicopter at half the gross weight of the Mi-10 had equal or slightly better slingload capability. Today, however, the "D" version of the Chinook can achieve VTOL payloads equal to the Mi-10 'gripper' loads which require a rolling takeoff (see Part 1, Table 5.1A).

Perhaps even more noticeable than the emphasis on ease of field maintenance is the fact that in Ref. 8, PHI made no mention of overhaul tours or limited life of the parts. According to Free[7], a team from British European Airways Helicopters found comparatively short overhead tours and retirement lives for Soviet helicopters. It is an interesting coincidence that this British team was in Moscow at almost the same time (February 1967) that PHI received the crated Mi-8 and Mi-10 helicopters from Russia. Unfortunately, as indicated in Ref. 7, while the British saw the Mi-10, they were more interested in the Mi-8 and thus, reported overhaul tours and retirement lives for only the smaller helicopters. Furthermore, the British apparently were interested more in airline operations and were not as concerned for field maintenance and remote area survivability as was PHI. The overhaul tours and retirement lives reported by Free for the Mi-8 are in good agreement with the information on the Mi-2 shown in Table 3.20 and Fig. 3.14. It must be assumed that since these helicopters are contemporary, if not earlier models than the Mi-10, its tours and service life would have been of the same order. But the absence of any reference by PHI to this aspect of maintainability of the Mi-10 indicates that their need for the giant helicopter was limited to the "hundreds of hours of flying time" of the evaluation.

__Questions Regarding the Soviet Approach to Maintainability.__ On review of the above data, many questions come to mind:

- How representative is the Mi-2 of the Soviet state of the art, even for helicopters of the same vintage?
- To what extent does the lower initial price of the Mi-2 (compared to the BO-105) compensate for the more frequent overhaul and replacement of major components?

- Are there other economic advantages to Soviet design for maintenance such as reduced labor for routine daily and periodic servicing and less unscheduled maintenance?

Such questions deserve an answer, particularly when we have seen in earlier sections that, in general, Western helicopters appear to be more efficient than their Soviet counterparts. Unfortunately, the available limited quantified maintenance data mitigates against complete answers at this time. However, perusal of the source material does provide some insight.

Just how representative are the Mi-2 maintenance characteristics? Free[7] indicated that overhaul tours for the Mi-8 started out at 500 hours for the main-rotor gearbox and that the rotor-blade life was 1000 hours. This was the exact order of magnitude that he was given for the Mi-2 when he visited Poland in the late 1960's. Free stresses in both Ref. 7 and in recent correspondence that the Soviets seem to move very cautiously in the areas of retirement life and overhaul tour extension.

Tishchenko[1] suggests that rotor-blade life must ultimately be at least 2000 hours, although he recognizes that the initial service life will be only "a few hundred hours." Contrast Tishchenko's expected 2000-hour life with the 10,000 and 30,000 blade retirement lives listed for Western helicopters. Similarly, Tishchenko refers to overhaul of major components of modern helicopters being performed every 1000 to 1500 hours. Thus, Tishchenko's high value compares with the initial value used for start-up on the recently certificated BV-234.

Does the lower initial price compensate for low tours and retirement life? The price of the Mi-2 is only 60 percent of that of the BO-105, but its blade retirement life and hub overhaul tour are only 10 percent of that of the BO-105. Even if it is assumed that the costs of replacement parts are in the same ratio as the initial costs, it is difficult to see how the Soviet system would prove more economical to the operator.

Are there other economic advantages to the Soviet concept? Investigation of this question has resulted in several revealing perceptions obtained in discussions with various experts. For example:

- When the state operates the factory that builds the helicopter and then becomes the operator of the helicopter in service, what national objectives are involved in the total process? Is it possible that factory employment (replacing the overhaul of helicopter components) takes precedence over the economics of transport operation?
- Civil use of helicopters in Russia is said to take place primarily in barren, remote areas where maintenance would be difficult. If the maintenance parameters are conservative by Western standards, and if the helicopters are rugged on a day-to-day basis, perhaps they can be used for long periods (1000 hours or 6 months) with very little maintenance support. Fetsko, an experienced helicopter maintenance expert, suggested that this might be the case. The PHI experience with the Mi-10 further reinforces this position.
- On the other hand, Tishchenko, Fetsko, and Polish helicopter engineers have suggested that the Soviet maintenance philosophy is changing. Overhaul tours are to be extended and retirement

lives increased. As previously indicated, the Polish Mi-2 engineers stated that they intend to increase rotor-blade life to 1800 hours when their license agreement with Russia permits. This is backed up by recent announcements in trade journals which indicate that the Soviets wish to change their international image of selling aviation products that are "barbarically expensive to operate[9]."

- Some of the reasons for Soviet helicopter maintenance philosophy are explained by Gregory[9] upon examination of the Mi-26 and during conversations with Tishchenko. "The Mi-26 is a conservative (though recent) product because it fits the Soviet system where incentives favor caution to avoid failure rather than risk-taking for big breakthroughs."

Conclusions. To the extent that overhaul tours and retirement life are indicative of helicopter maintainability, the Soviet Mi-2 is inferior to its Western counterpart, the BO-105, and to larger Western helicopters of the same vintage. There is also persistent evidence that Soviet designers feel obligated to take a low-risk approach, resulting in cautious extension of overhaul tours and retirement life; however, Soviet helicopters are designed to be trouble-free and self-sustaining for operations in remote areas.

It can be hypothesized that industrial design in the USSR is governed by broad national goals such as employment levels rather than operational economics. From a military standpoint, short replacement times may assure that personnel in technical support of helicopters are given adequate field experience in this aspect of maintenance. It should be noted that with U.S. designs having substantially longer replacement requirements, much of the 'mean time between removal' information on U.S. military helicopters may be attributed to on-the-job training of short-term enlistees.

The motives implicit in Western design for maintenance (long tours, long service life) should be scrutinized. Although this approach in commercial-type operations contributes to a lower operating cost, it is not a'priori clear that it is also appropriate to achieving the most cost-effective military helicopter for the U.S. Army. Is it possible that, regardless of the area of application, Western aeronautical technology has blindly pursued sophistication, with not enough emphasis on the importance of simplicity?

Credits and Acknowledgements

Section 3.4 was compiled with the assistance of Mr. Lloyd H. Sloan of Lloyd H. Sloan and Associates of Bellevue, Washington, who researched much of the material cited in the text and conducted many personal interviews with such knowledgeable people as F.W. Free who was responsible for technical and economic evaluation of helicopters for the then British European Airways Helicopters. It would be remiss not to also acknowledge with gratitude the courtesy and cooperation of Mr. Jack Fetsko, President of Spitfire Helicopter Co., Ltd., of Media, Pa., who made available brochures and a maintenance manual for the Polish-built Mil Mi-2. Other sources who contributed to the validity of the data contained in this section were the MBB Helicopter Corporation of West Chester, Pa., which made available rather complete information on the MBB BO-105 helicopter; and Boeing Vertol Co. of Philadelphia, Pa., which provided information on the recently certified commercial version of the CH-47 'Chinook' helicopter. Finally, credit must be given to Columbia Helicopters, Inc., of Portland, Oregon for updating the maintenance data on the BV-107 (CH-46) helicopter.

3.5 Evaluation of the Rotor System Design

General Remarks. Comparisons of helicopters as a whole are usually conducted on the basis of their flight performance, weight aspects, vibration levels, and many other characteristics that are, as a rule, expressed in figures available to the evaluator.

But when it comes to a comparison of the design aspects of major components, usually one can find only general descriptions, and a few figures, which leave many factors undefined in their magnitude of importance.

In light of this situation, it would be desirable to develop a method of evaluating various design features of components and to present them in numerical form, thus permitting one to rank the various components of the compared helicopters on a quantitative basis.

There are obviously many possible ways of achieving this goal. The one attempted in this study consists of identifying various design features of a major component and assigning them "merit points" wherein the total would provide a gauge for assessing the excellence of the design according to the accepted criteria.

As can be seen from the preceding sections, there are nine assemblies (excluding engines) which, in the weight studies, were identified as major helicopter components. A thorough evaluation and rating of each component for the twenty-three actual, plus some hypothetical helicopters considered in Part I would carry this study beyond its intended size. Consequently, it was decided to concentrate on the most vital ingredient of any helicopter – namely, on the rotor system as represented by the blade-hub assembly, and to limit the number of compared helicopters to the three pairs (Mi-2–BO-105, Mi-8–UH-60A, and Mi-6–CH-53E) investigated in Chapter 2 of this volume.

Blade Index of Merit. Blades of the Soviet and Western helicopters compared in this study are evaluated with the assistance of the Index-of-Merit table (Table 3.21). Justification of the point values appearing in this table is presented below:

As in every case wherein the evaluation of advantages and disadvantages of any product is the prime objective, the final table may reflect the individual opinion of the evaluator. In order to reduce this possibility to the bare minimum, a "List of Importance" is to be compiled.

There is no doubt that the structural integrity of the blade should head the list. But it is difficult to express this value in terms of blade life (either calculated or guaranteed) because the often-claimed infinite life is not met in practice, and the projected limited number of blade-life hours are often misleading and, as they depend on mission profile, are often unobtainable. Therefore, instead of using blade life as the index of structural integrity (or reliability), the actual structural material of the blade will be used for evaluation. This information is available and should not create any controversy.

Four structural materials are being used in the blades subjected to evaluation: aluminum alloy, steel, titanium, and fiber-reinforced plastics. They are listed in growing order of structural reliability. However, their value can not be listed in strict numerical order (1, 2, 3,...). Instead, it would be more appropriate to rate them according to the scale shown in Table 3.21. The reason for such a wide gap between

TABLE 3.21

INDEX OF MERIT
BLADE EVALUATION TABLE

BLADE TYPE		MERIT POINTS
Aluminum Alloy Extruded Spar		10
Aluminum Alloy Extruded Spar with BIM*		20
Steel "D" Or Oval (Mi-6 Spar)		15
Steel "D" or Oval Spar with BIM*		25
Titanium Spar		25
Titanium Spar with BIM*		40
Fibre Reinforced Plastic		65
Fibre Reinforced Plastic with BIM*		66
ADDITIONAL FEATURES		
Safety	redundancy	12
	deicing	7
	lightning protection	5
Weight		0 – 4
Acoustics		2
Field Repairability		0 – 2
Reproducibility		0 – 2
Maximum Points		100

*Blade Inspection Method (BIM)

the three metals and FRP (fiber-reinforced plastics) is the crystalline structure of metals which is prone to low fatigue properties, notch sensitivity, and corrosion. In the metals group, aluminum alloy is rated lowest because of the requirement of very stringent quality control of extrusions (the form in which aluminum alloy blade spars are commonly used), especially in the case of porthole or stepped extrusions. Also, soft aluminum alloy extrusions are vulnerable to sand erosion and require special protection.

From this viewpoint, steel is superior but shares common problems with other metals (for example, impurities, folds, etc.) that further lowers the fatigue properties and notch sensitivity.

Titanium, rated at the top of the metals group, offers a better strength-to-weight ratio and is less sensitive to corrosion.

There will be no rating of the various kinds of fibers in the FRP group; i.e., E-glass, S-glass, and a few types of carbon and boron. Although some offer better strength-to-weight ratios, others are inferior

due to brittleness (ballistic damage vulnerability), but all of them as a group are far superior to metals as far as structural integrity and flight safety is concerned. Consequently, they will be rated as one group.

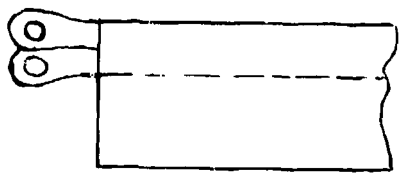
Other features of the blades which affect their rating in the Index of Merit are more controversial in their sequence of importance. They include:

(1) redundant structure
(2) failure warning
(3) de-icing
(4) lightning protection
(5) weight
(6) acoustics
(7) field repairability
(8) reproducibility

The first four features pertain to flight safety; consequently, they will generally be marked with higher points in blade classification.

(1) redundant structure. It is impractical to design whole blades as a redundant structure without taking into consideration the large weight penalty involved. Therefore, all efforts aimed at redundancy should be directed toward the most vulnerable spot; i.e., the root-end attachment. Regardless of the structural material used, the transfer of load from one element of the rotor system (blade) to another (hub) constitutes a challenge for the designer.

In metal blades, some degree of redundancy is usually achieved – either by a two-bolt attachment or by a multiple-bolt pattern on the periphery of the root-end flange. In the case of FRP, redundancy may be obtained by two wrap-around pin attachments (two pins in chordwise position).



The Aerospatiale SA365N uses a simple method of splitting the layers of the FRP solid spar (extending from the leading edge to 20 percent chord) into two loops as shown above.

Boeing Vertol achieves the same goal by a more elaborate layup, extending inboard from a hollowed D-spar, which is a more efficient design.

(2) **failure warning.** Early metal blades manufactured by Sikorsky (aluminum alloy extrusions, leading-edge porthold extrusions on the first models, and over-the-mandrel extrusions on subsequent models), and Boeing Vertol (leading-edge steel "D" spar) were pestered by fatigue failures. To remedy this situation, Sikorsky introduced the spar-pressurized systems called BIM (blade inspection method), where the development of cracks resulting in a loss of pressure in the spar was signaled to the crew. Boeing Vertol followed by a vacuum-based warning system (ISIS). Both methods provide an adequate warning to prevent catastrophy.

(3) deicing. Blade deicing is a must if the helicopter is going to be used in all-weather flying conditions. Deicing is usually achieved by covering the blade leading edge with an electrically-heated blanket protected by metal leading-edge strips.

(4) lightning protection. Blade lightning protection is being regarded as a standard feature on most of the recently produced blades, extending their all-weather flying capabilities.

(5) weight. Blade weight plays an important role in the weight breakdown of the weight empty of any helicopter because it has a snowballing effect on the rotor system by virtue of the fact that heavier blades require heavier hubs. The question is how to evaluate the weight of one blade against another. Chordwise balancing has a definite effect on blade weight. So is the way that the dynamic balance is achieved (station-by-station or tip overbalance). For the sake of simplicity, the blade weight index is related to the ratio of total blade weight to the maximum flying gross weight of the helicopter in the following way: Blades having relative weights higher than 6 percent of the maximum flying gross weight will not be awarded any points. One point is awarded for each percent below this 6 percent value.

(6) acoustics. More and more attention is being focused on the acoustic characteristics of blades. Although the efficiency of different devices can not be evaluated properly at the present time, their presence at the blade tip is easily spotted, and this fact should be noted in the Index of Merit.

(7) field repairability. Field repairs are generally easier in the case of FRP, although some designs such as segmented blade elements attached to the spar constitute an exception (Mil-6 design).

(8) reproducibility. The design of a new efficient airfoil offering a significant improvement of properties verified in wind tunnels is the problem of aerodynamicists. But the reproduction of wind-tunnel airfoils machined to very close tolerances into full-scale airfoils is another problem that must be solved by manufacturing experts. Although reproducibility depends on blade design (some designs are more suitable for reproduction to close tolerances than others), and on manufacturing techniques, one thing is certain: FRP offers pronounced advantages in this field.

It should be noted that some blade characteristics, although important and interesting, are omitted in the proposed evaluation. For instance:

(a) blade airfoils. The use of advanced airfoils such as the VR7 and VR8 constitute an important step in the development of the rotor system. But they are not rated in the Index of Merit table because their contribution has already been reflected in such helicopter performance as speed, ceiling, and lifting capability.

(b) blade dynamic properties. Information concerning the blade balancing method is difficult to obtain (especially from Soviet sources). So are natural frequencies.

(c) blade cost. Even if this information were available from Soviet sources, it would be meaningless due to unrealistic currency exchanges.

Consequently, only those blade features that are readily available from Soviet sources, publications (Jane's or magazines), and Soviet books are taken into consideration.

It should be noted that some features are rated differently in different groups. For instance, failure warning (BIM) is very important in metal blades and therefore is rated highly, whereas in FRP, it plays a minimal role because of the low notch sensitivity of the structure and very slow crack propagation.

Similarly, field repairability of Mil-6 full-chord blade segments will be rated much higher than that of trailing-edge boxes of the "D" spar design.

Finally, it should be noted that the Index of Merit range in Table 3.21 for the four groups of blades evaluated in this study extends from 10 to 100.

Merit Index for Hubs. The hub of any helicopter is a component that is usually heavy, complicated, requires lots of maintenance, presents considerable drag and, last but not least, is very expensive.

The hub of fully articulated blades with its three axes of rotation, multitude of bearings, and hundreds of components has been a source of potential failure which, in rough terms, will be a function of the quantity of joints and bearings. Therefore, this type of hub is given the lowest Index-of-Merit rating. The teetering hub features a reduced number of components and bearings; consequently, it is rated higher. Further reduction in the number of components was achieved in the nonarticulated (hingeless) rotor system which eliminates flapping and lead-lag hinges, leaving only pitch bearings in the hub. This type of rotor system is very attractive in the case of the single-rotor helicopter (large hub moments, allowing for extensive c.g. travel). However, it seems to be impractical in application to tandem and side-by-side rotor configurations where yaw control requires a large tip-path inclination with respect to the rotor axis.

The introduction of tension-torsion systems, replacing highly-loaded thrust bearings in the pitch-bearing housing, has had a beneficial effect on reliability and maintenance of the helicopter hub.

Replacement of antifriction bearings of all types (ball, roller, or taper roller) by elastomeric bearings was a significant step forward in hub design. It radically reduced maintenance and dramatically increased the reliability of the system.

Spherical elastomeric bearings allowed the replacement of three axes bearings by one performing all three movements: flapping, lead-lag, and pitching.

Redundancy of hub elements was (and is) a seldom-found feature in helicopter design and, whenever applied, should be recognized as a significant improvement. So far, such a feature is incorporated in the design of the Boeing-Vertol UTTAS YUH-61A pitch-bearing housing where, in the event of tension-torsion strap failure, the shaft will be retained by a mechanical stop (flange butting against the housing). Another example of hub redundancy is the Boeing Vertol HLH XCH-62A, where the spherical elastomeric bearing is retained by a redundantly designed yoke.

Success with fiber-reinforced plastic blades prompted the idea of using fibrous materials in the design of the hub proper. This step increased the reliability, and reduced the weight and even the drag of the hub. The ultimate goal of a bearingless hub was made possible only by the use of fiber-reinforced plastic as a structural material. There is no doubt that the bearingless hub constitutes a breakthrough in helicopter technology.

At the present time, the nearest to the ultimate goal is Boeing Vertol's solution as flown on the BO-105, which takes the load of the pitch actuator (UNIBALL bearing). However, there are discontinuities of the structure: joints between the blade and flex-straps, and between the flex-straps and the hub proper. Elimination of all these joints would be possible only in the case of a small diameter rotor in which the hubless blade would extend from tip to tip; molded as one unit from fiber-reinforced plastic

The philosophy outlined above is reflected in the selection of the merit-point values shown in Table 3.22. It should be noted that in the proposed scheme, the range of points for the general configuration of the hub would extend from 10 to 75, with an additional 25 points maximum awarded for weight classification. Here, 5 weight points would be given for each percentage of weight-saving between 8 percent and 3 percent of the maximum flying gross weight. (These values resulted from a survey of the relative hub weights which indicated a range of 3.6 to 7.8 percent of the maximum flying gross weight.) In this way, the maximum number of points which can be awarded for the hub design would not go above 100.

TABLE 3.22

INDEX OF MERIT FOR HUB EVALUATION

HUB TYPE	INDEX
Fully articulated hub with antifriction bearings	10
Fully articulated hub with antifriction bearings and T–T strap	13
Teetering hub (underslung feathering axis)	18
Teetering hub (underslung feathering axis) and T–T strap	21
Hingeless hub (Boelkow)	27
Hingeless hub with redundancy features (B–V H60)	30
Elastomeric bearings (fully articulated, 3 separate bearings)	35
Combination of spherical and radial elastomeric bearings	40
Single elastomeric spherical bearing	43
Single elastomeric spherical bearing with redundancy	48
FRP hub, fully articulated, with elastomeric bearing	55
FRP hub, fully articulated, with single spherical elastomeric bearing	60
Bearingless main rotor hub (B–V, BMR)	70*
Bearingless hub with no bearings or structural joints	75*

*Not applicable to helicopters being considered at this time.

Blade and Hub Indices of Merit. Blade and hub indices of merit for the three compared pairs of Soviet and Western helicopters are computed in Tables 3.23 and 3.24, respectively. The results of the evaluations are graphically presented in Fig. 3.15.

From an overall design viewpoint, one can determine from this figure and tables that according to previously established criteria, the blades and hubs of the compared Soviet helicopters appear to be inferior to their Western counterparts. However, it should once more be emphasized that the criteria used here represents only an initial attempt to quantitatively evaluate the overall merits of design of major helicopter components. Thus, because of the heretofore uncharted approach, controversy may exist; not only regarding the number of points that should be awarded for various design features, but also the selection of the design characteristics considered important may be questioned. Nevertheless, it is believed that in spite of these reservations, the basic approach presented here is valid, and should be further developed and improved.

Credits and Acknowledgements

Section 3.5 was completed with the assistance of Mr. T. Tarczynski, Aeronautical Consultant, of Ridley Park, Pa., who developed the method and constructed the tables for the indices-of-merit evaluation. Also the contributions and suggestions from Dr. Richard Carlson and Mr. Frederick Immen of the U.S. Army Research & Technology Laboratories, Ames Research center are acknowledged with gratitude.

TABLE 3.23

BLADE INDEX OF MERIT

ITEM	HELICOPTER					
	Mi-2	BO-105	Mi-8	UH-60A	Mi-6	CH-53E
Max. Gross Weight; lb	8175	5114	26,455	20,250	93,700	73,500
Weight of Rotor Blades lb	364	268	1477*	341	5951**	2888.9
Percentage of Max. GW	4.45	5.24	5.58	4.95	6.35	3.92
	MERIT EVALUATION POINTS					
BASIC MATERIALS						
Aluminum Alloy Extrusion	10		10			
Steel					15	
Titanium				25		25
Fiber-Reinforced Plastic		65				
DESIGN FEATURES						
Redundancy						
De-Icing	6		6	6	6	6
Lightning Protection				5	5	5
Weight Index	2	1		2		2
Acoustic Features				1		1
Field Repairability	1		1	1	1	1
Reproducibility	1	2	1		1	
Blade Inspection Method	10		10	15	10	15
INDEX OF MERIT	30	68	28	55	38	55

Notes: *Extruded aluminum spars

**Lighter blades[1]

TABLE 3.24

HUB INDEX OF MERIT

ITEM	HELICOPTER					
	Mi-2	BO-105	Mi-8	UH-60A	Mi-6	CH-53E
Max. Gross Weight; lb	8175	5114	26,455	20,250	93,700	73,500
Weight of Rotor Blades; lb	291.1	200.5	1333.0	605.9	7331.6	3472.1
Percentage of Max. GW	3.56	3.92	5.03	2.99	7.82	4.72
MERIT EVALUATION POINTS						
DESIGN FEATURES						
Fully articulated hub with anti-friction bearings	10		10		10	
Hingeless hub		27				
Single elastomeric spherical bearing				43		43
Weight Index	22	20	15	25	1	16
INDEX OF MERIT	32	47	25	68	11	59

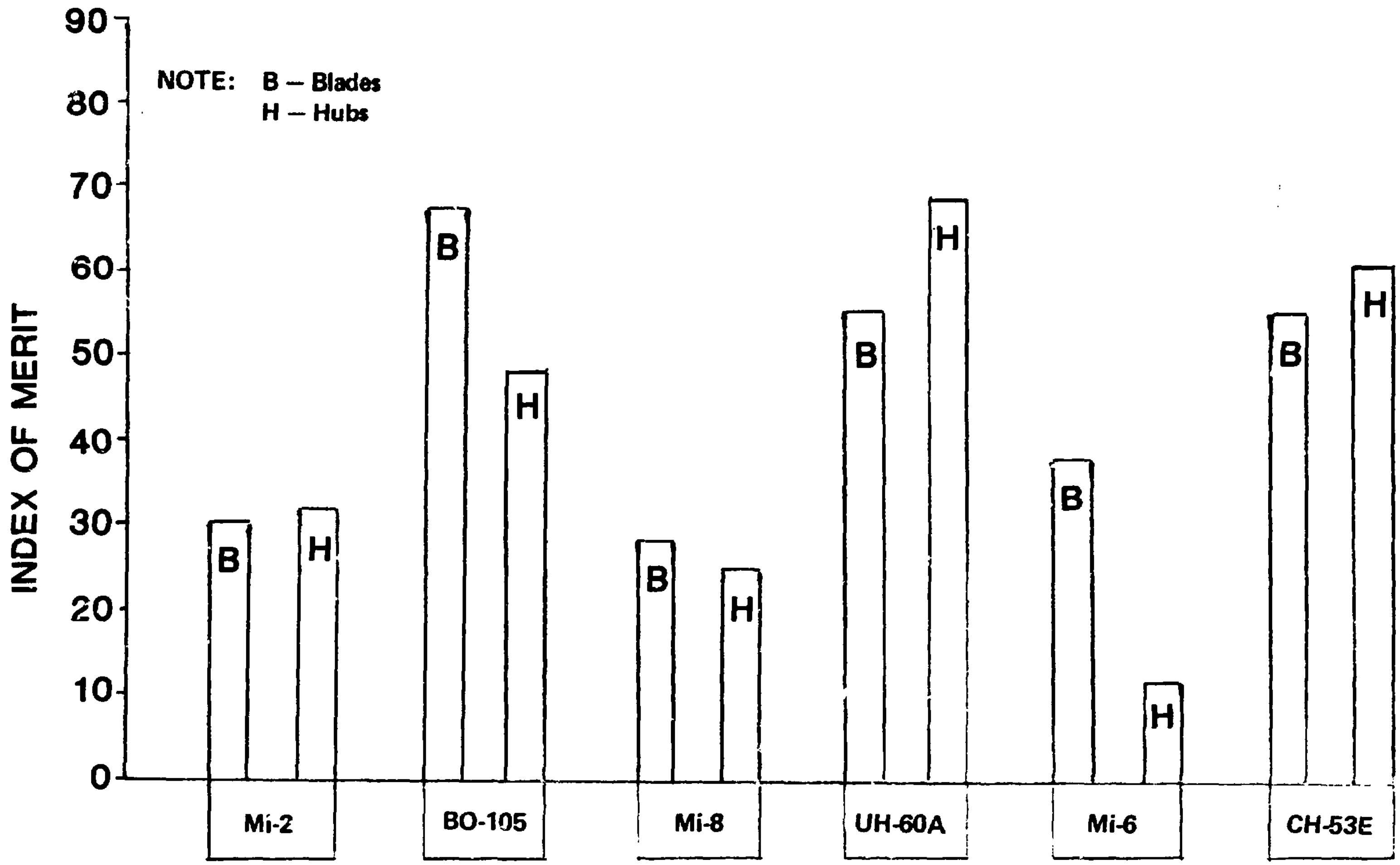


Figure 3.15 Blade and hub indexes of merit for three pairs of Soviet and Western helicopters

APPENDIX TO CHAPTER 3

RELATIVE COMPONENT WEIGHT TRENDS
KEY TO TRANSPORT HELICOPTER CONFIGURATION RATINGS

Introduction. Tishchenko, et al[1] rated various configurations having gross weights up to 60 m.tons for transport operations as follows: first, single rotors, second, side-by-side; and third, tandems. They did this by using maximization of the payload over both short (50 km) and long (800 km) ranges as illustrated by summary graphs (Figs. 2.86 and 2.87[1]) which are reproduced here as Figs. A-1 and A-2. Fig. A-1 shows the dependence of payload transported by the optimal variants on gross weights of various helicopter operations, while Fig. A-2 depicts the percentage of weight output and relative payload for optimal variants, again as a function of gross weight.

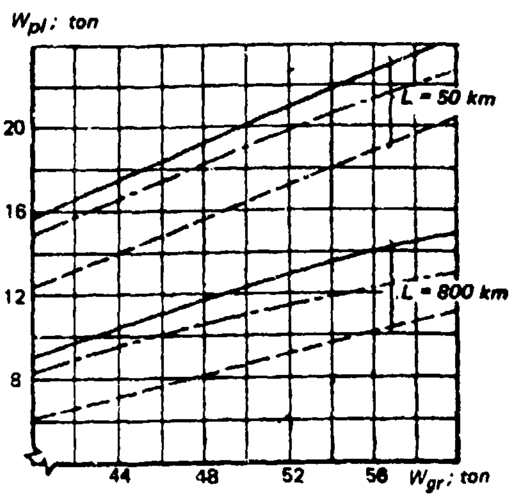


Figure A-1 Dependence of payload on GW

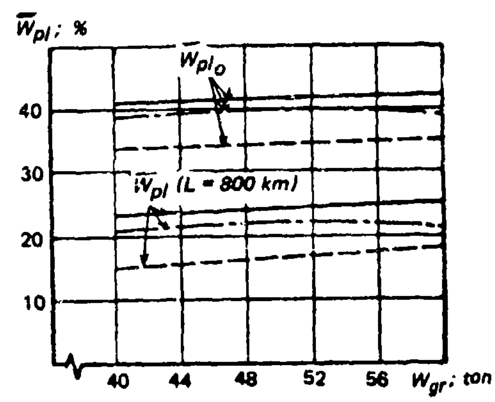


Figure A-2 Percentage of weight output and relative payload as a function of GW

NOTE: ——— single-rotor helicopter ($n_{bl} = 8$); — — —tandem ($n_{bl} = 5 \times 2$); — · — — -side-by-side ($n_{bl} = 8 \times 2$)

In studies conducted in Section 3.3, it became apparent that many of the relative weight trends of the major components appearing in Ref. 1 were higher for their hypothetical tandems than for their single-rotor counterparts. Furthermore, the trends assumed in Ref. 1 for hypothetical helicopters were at variance with that established by the same components existing in current Western tandems and single-rotor machines. Due to the lack of actual design experience in the West regarding large side-by-side transport helicopters, the trends established in Ref. 1 must go unchallenged.

Using the Soviet hypothetical major component weight trends, computations were performed in order to investigate whether these trends were the key to the differences in the relative payload weights shown in Fig. A-2 and the resulting rating of the configurations. Once this was done, the question remains as to what would be the effect on those relative payload values should trends based on actual Western designs be applied.

Relationship between Relative Payload and Relative Major Component Weights. The gross weight of a helicopter prepared for flight carrying a given payload (W_{pl}) over a given distance can be expressed as follows:

$$W_{gr} = W_{pl} + \sum_{1}^{9} W_{cn} + W_{eng} + W_{fu} + W_{eqp} + W_{crew} \quad \text{(A-1)}$$

where $\sum_{1}^{9} W_{cn}$ is the weight of all the nine major components, whose relative weights were discussed in this chapter; W_{eng} is the weight of installed engines (excluding weight of the propulsion subsystem, which is already included under the Σ sign); W_{fu} is the weight of fuel required for a given range; W_{eqp} is the weight of equipment and instrumentation; and W_{crew} is the weight of the crew.

Dividing both sides of Eq. (A.1) by W_{gr} and denoting relative weights by a bar over W, the following expression for the relative payload is obtained:

$$\overline{W}_{pl} = 1 - \left(\sum_{1}^{9} \overline{W}_{cn} + \overline{W}_{eng} + \overline{W}_{fu} + \overline{W}_{eqp} + \overline{W}_{crew}\right) \quad \text{(A-2)}$$

Differences in $\overline{W}_{pl}$ for Various Configurations. Using Eq (A-2), differences in the relative payload between configurations; say, between single-rotor and tandem, can be expressed as follows:

$$\overline{W}_{pl_{sr}} - \overline{W}_{pl_{tan}} = \sum_{1}^{9}\left(\overline{W}_{cn_{sr}} - \overline{W}_{cn_{tan}}\right) + (\overline{W}_{eng_{sr}} - \overline{W}_{eng_{tan}}) +$$

$$+ (\overline{W}_{fu_{sr}} - \overline{W}_{fu_{tan}}) + (\overline{W}_{eqp_{sr}} - \overline{W}_{eqp_{tan}}) + (\overline{W}_{crew_{sr}} - \overline{W}_{crew_{tan}}) \quad \text{(A-3)}$$

It is highly probable that the actual weights of crew and equipment for different helicopter configurations of the same design or maximum flying gross weights would be the same. This would obviously also apply to relative weights. Consequently, it is permissible to take the last two terms in Eq. (A-3) as equal to zero.

The data necessary to examine possible differences in the relative engine group weights of Soviet hypothetical helicopters is shown in Table A-1, which is based on inputs from Table 2.8 and Figs. 2.79, 2.82, and 2.85 – all from Ref. 1.

Looking at this table, one can see that on the average, $\overline{W}_{eng_{sr}} - \overline{W}_{eng_{tan}} = -0.4\%$, and $\overline{W}_{eng_{sr}} - \overline{W}_{eng_{sbs}} = 0.38\%$.

The relative fuel weights required for the 800 km flight distance with regard to the Soviet hypothetical 52 m.ton gross-weight configurations considered in this study are directly obtainable from Figs. 2.79, 2.82, and 2.85 in Ref. 1. However, for the 15 m.ton gross-weight single rotor and tandems, the fuel required is only given for a distance of 370 km (Table 2.8[1]). In order to obtain the relative fuel weight for the common flight distance of 800 km, the quantities given in this table are multiplied by a factor of 800/375 ≈ 2.13. The fuel quantities obtained in this way, along with those for the 52 m.ton gross-weight class are shown in Table A-2.

TABLE A-1

SOVIET HYPOTHETICAL HELICOPTERS
EXPLICIT AND RELATIVE ENGINE INSTALLATION WEIGHTS

Hypothetical Helicopter	ENGINE INSTALLATION WEIGHTS, KG OR %		
	Explicit	Relative	Relative Average
15 m.ton Single Rotor	790	5.27	Single Rotor 5.76
15 m.ton Tandem	940	6.27	
52 m.ton Single Rotor	3250	6.25	Tandem 6.16
52 m.ton Tandem	3150	6.06	
52 m.ton Side-by-Side	2800	5.38	Side-by-Side 5.38

TABLE A-2

SOVIET HYPOTHETICAL HELICOPTERS
EXPLICIT AND RELATIVE FUEL WEIGHTS REQUIRED FOR 800-KM RANGE

Hypothetical Helicopter	FUEL WEIGHTS, KG OR %		
	Explicit	Relative	Relative Average
15 m.ton Single Rotor	3089	20.59	Single Rotor 18.76
15 m.ton Tandem	3195	21.30	
52 m.ton Single Rotor	8800	16.92	Tandem 19.02
52 m.ton Tandem	8700	16.73	
52 m.ton Side-by-Side	9500	18.27	Side-by-Side 18.27

It can be seen from Table A-2 that on the average, $\overline{W}_{fu_{sr}} - \overline{W}_{fu_{tan}}$ = -0.26%. However, for large helicopters, this difference amounts to 0.19% – this time in favor of the tandem. In view of this situation, the influence of the quantity of fuel on the $(\overline{W}_{pl_{sr}} - \overline{W}_{pl_{tan}})$ values may be neglected. However, the difference in fuel weight for the single-rotor – side-by-side pair is 0.49%; therefore, in this case the difference may be taken into consideration when determining the $(\overline{W}_{pl_{sr}} - \overline{W}_{pl_{sbs}})$ values.

TABLE A-3

SOVIET HYPOTHETICAL HELICOPTERS
RELATIVE MAJOR COMPONENT WEIGHT TRENDS
(AT DESIGN GROSS WEIGHTS)

ITEM	Relative Component Weight related to Design GW; %		
	Single Rotor	Tandem	Side-by-Side
1. Main-Rotor Blades	6.23	5.90	4.04
2. Main-Rotor Hubs & Hinges	4.83	5.85	4.85
3. Drive System	8.80	11.11	10.12
4. Fuselage	11.44	14.24	15.10
5. Landing Gear	2.54	2.77	2.98
6. Flight-Control Group	3.47	4.51	2.88
7. Tail-Rotor Group	1.27	–	–
8. Fuel System	1.62	1.71	1.54
9. Propulsion Subsystem	2.16	2.10	1.86
$\sum_{1}^{9} W_{cn}$	41.36	48.19	43.37
$\sum_{1}^{9} (W_{cn})_{sr} - \sum_{1}^{9} (W_{cn})_{tan}$	–	−6.83	–
$\sum_{1}^{9} (W_{cn})_{sr} - \sum_{1}^{9} (W_{cn})_{sbs}$	–	–	−2.01

The next step was to compute the difference in $\sum_{1}^{9} W_{cn}$ of various Soviet hypothetical helicopters. This was done in Table A-3 for design gross weights using data from Tables 3.11 through 3.19. Limiting this investigation to the design weight case only is justified by the fact that the maximum flying weights for Soviet hypothetical helicopters were established somewhat arbitrarily and furthermore, both the actual and relative payload considerations contained in Ref. 1 were related to nominal gross weights (e.g., 15 or 52 m.ton), which appear to correspond to the design gross weights. It is shown in this table that the differences in relative weights of the nine major helicopter components would amount to 6.83% in favor of the single-rotor configuration when compared with the tandem, and 2.01 percent when compared with the side-by-side configuration.

Looking back at Fig. A-2, one will find that based on design gross weight, the percentile advantage in the relative payload foreseen for the single-rotor transport helicopter would amount to about 7% over the tandem, and about 2% over side-by-side configurations in the 40 to 52 m.ton design gross-weight class. These figures are so close to the 6.83% and 2.01% respectively, of the major component relative weight advantages for the single-rotor helicopter that one can see from this case that, indeed, relative component weights represent a key to payload advantages. Consequently, it is clear that should the relative weight trends of the major components assumed by Tishchenko et al be correct, then the ratings of the various configurations would also be correct.

In order to check this point, differences in the relative weights of the major components between the configurations were examined, using trends exhibited by actual Western helicopters. Because of the absence of large side-by-side helicopters in the West, this comparison is, of necessity, limited to the single-rotor vs. tandem designs.

Table A-4 was constructed using the data from Tables 3.11 through 3.19. Contrary to the trend shown by Tishchenko et al for hypothetical Soviet helicopters, actual experience in the West indicates that an advantage in the relative weights of the major components may be expected for tandems when compared with single-rotor configurations. The results given in Tables A-3 and A-4 are also graphically presented in Fig. A-3, which visually illustrates the point that actual experience with Western helicopters tends to contradict the trends assumed by Tishchenko et al for their hypothetical helicopters regarding the advantage of the single-rotor configuration over the tandem with respect to the summary relative weights of the major components.

Concluding Remarks. In their study of hypothetical helicopters, Tishchenko et al[1] indicated that for transports of the 40 to 60 m.ton gross-weight class, the single-rotor configuration should have an advantage in payload-carrying capability amounting to about 7% of gross weight over that of the tandem, and about 2% more than for the side-by-side configuration. These same percentile advantages were claimed for both short (50 km) and long (800 km) ranges.

During the process of verifying the above configuration ratings, it was found that the relative weights of the major components have first-order effects on the differences in the relative payload-carrying capabilities of various configurations. Once this relationship was proven, it became possible to examine the validity of Tishchenko's configuration rating by comparing the trends projected in Ref. 1 with those indicated by actual Western helicopter designs.

Using the relative major component weight trends based on current Western helicopters, it was shown that for the transport missions considered in Ref. 1, the tandem should not be inferior in relative payload-carrying capacity when compared with the single-rotor configuration, but contrary to the projections of Tishchenko et al, it may even have an advantage which, as computed on the basis of the somewhat limited statistical data, could amount to about 3.4% when maximum flying gross weight is used as a reference.

TABLE A-4

EXISTING WESTERN SINGLE-ROTOR AND TANDEM HELICOPTERS
DETERMINATION OF DIFFERENCES IN RELATIVE WEIGHT TRENDS OF MAJOR COMPONENTS

ITEM	Relative Component Weights of Western Helicopters; %			
	Single-Rotor		Tandem	
	Design GW	Max. Flying GW	Design GW	Max. Flying GW
1. Main-Rotor Blades	5.53	4.44	5.15	4.25
2. Main-Rotor Hubs & Hinges	4.47	3.57	4.88	4.00
3. Drive System	10.46	8.34	9.41	7.79
4. Fuselage	13.89	11.14	9.35	7.76
5. Landing Gear	2.67	2.09	2.63	2.25
6. Flight-Control Group	4.75	3.82	4.40	3.62
7. Tail-Rotor Group	0.71	0.57	–	–
8. Fuel System	2.15	1.71	3.49	2.91
9. Propulsion Subsystem	1.01	0.82	0.63	0.52
$\sum_{1}^{9} W_{cn}$	45.64	36.50	39.94	33.10
$\sum_{1}^{9} (W_{cn})_{sr} - \sum_{1}^{9} (W_{cn})_{tan}$	–	–	5.70	3.40

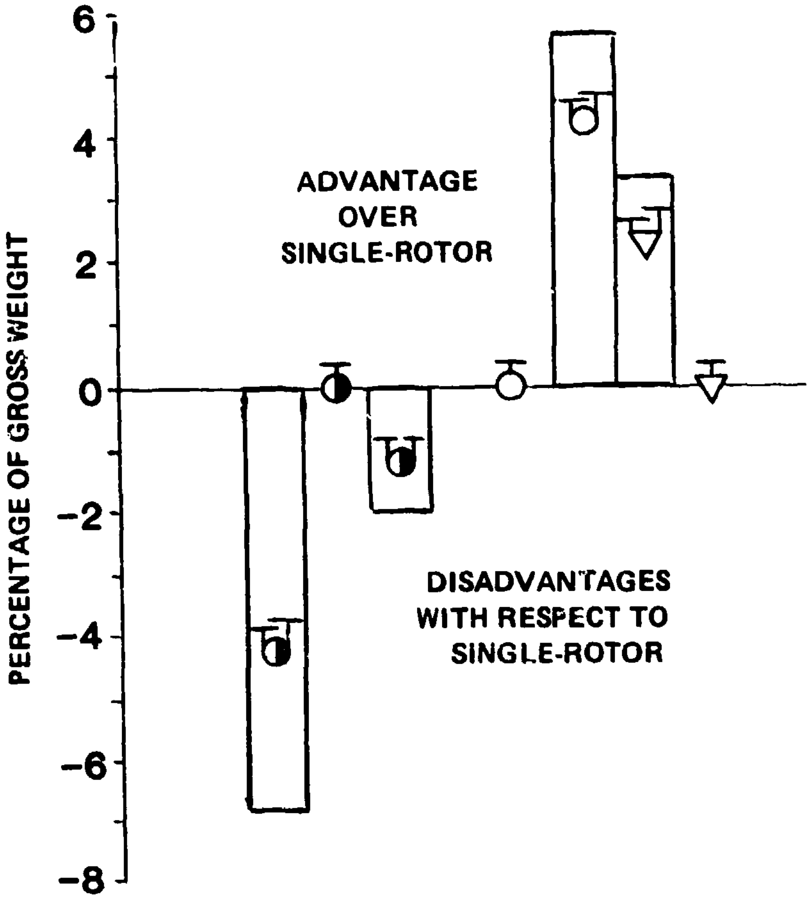


Figure A-3 Differences in the relative weights of the major components for tandem and side-by-side configurations with respect to those for corresponding single-rotor configurations

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15. Supplementary Notes

Point of Contact: W.D. Mosher, MS:207-5, Ames Research Center, Moffett Field, CA 94035 FTS 448-5578 or 415-965-5578

Reviewer R. Shinn

16. Abstract

This study provides a detailed comparative insight into design and operational philosophies of Soviet vs. Western Helicopters. This is accomplished by examining conceptual approaches, productibility and maintainability, and weight trends/prediction methodology. Extensive use of Soviet methodology (Tishchenko) to various weight classes of helicopters is compared to the results of using Western based methodology.

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